Assessment of the geothermal resources of the Republic of the Sudan

Jafar Sharafeldeen Albagir Mohammad

A Thesis Submitted in Fulfillment of the Requirements for the Degree of
Master of Science in Sustainable Energy Management
Prince of Songkla University
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Author	Mr. Jafar Sharafeldeen Albagir Mohammad
Major Program	Sustainable Energy Management

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I hereby certify that this work has not been accepted in substance for any degree and is not being currently submitted in candidature for any degree.

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ABSTRACT

There is an unavoidable need to develop geothermal resources to supplement Sudan's long-term energy demands significantly. Geothermal energy is one of the oldest, most varied, and widely utilized forms of renewable energy. As an introduction, an overview of geothermal energy, geothermal systems, the geological setting of East Africa, and the geological setting of Sudan will be explained. Following this, geothermal exploration in Eastern Africa and in Sudan will be presented. Many researchers have emphasized the significance of Sudan's geothermal resources, but due to a lack of knowledge, confidence, and authority, no actual work has been done, except the Bauyda area. A project in 1992 by ACRES concluded the highest potential in Jebel Marra, Red Sea, Muglad Rift Basin, and Bauyda Volcanic Field. As a result of the ACRES finding, this study focused on those areas to assess and rank them, although many potential geothermal resource areas have been identified and mentioned in previous reports. The positive attitude factors method was applied for potential geothermal areas in the republic of Sudan to assess and rank them. The positive attitude factors design method integrates past exploration data, reservoir, land uses, and marketing factors. An assessment and ranking of potential areas will mitigate the risk accompanied by resource development stages; therefore, this research will pave the way for decision-makers, private sectors, and stakeholders to lay out a roadmap for the development of geothermal resources of Sudan by focusing on the most promising sites. The final ranking shows that the Bauyda Volcanic Field has a good potential for further development. Therefore, research budgets and financial investments for geothermal exploration and development should be directed, followed by the Muglad Rift Basin area, Jebel Marra area, and the Red Sea area, respectively.

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LIST OF ABBREVIATIONS AND SYMBOLS

ACRES	Acres International Ltd. (Canada); in 2005 changed to Hatch Acres Ltd.; engineering company
BVF	Bayuda volcanic fields
EARS	East African Rift System
EGS	Enhanced geothermal systems
EOR	Enhance oil recovery
EREX	Earth Resources Exploration Group
GW	Gigawatt
GWe	Gigawatt electric
HDR	Hot Dry Rocks
KEMA	Keuring van Elektrotechnische Materialen te Arnhem (global energy consultancy company)
KenGen	Kenya Electricity Generating Company PLC
kV	Kilovolt
kW	Kilowatts
L/s	Liters per second
m.y.a.	Million years ago
MENA	Middle East and North African
mGal	Milligal
MODIS	Moderate Resolution Imaging Spectroradiometer
MT	Magnetotelluric
MW	Megawatt
MWe	Megawatt electric
PGRAS	Potential geothermal resource area of Sudan
RSPOC	Red Sea Petroleum Operating Company
TEM	Transient electromagnetic
UNAMID	United Nations–African Union Mission in Darfur
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey

LIST OF PUBLICATIONS

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CHAPTER 1
LITERATURE REVIEW

1. Introduction

Energy is one of the main parameters that drives and is an important cornerstone in a country’s economic and social development. Decades of fossil fuel consumption however have shown that the emitted greenhouse gases, like CO2, have resulted in climate change processes, which are still going on and likely to increase. However, energy sources that are not emitting greenhouse gases, or very small amounts, are available, like wind, solar, hydropower, and geothermal, and others, all summarized under renewable energy. The availability of each renewable energy source in each country depends often on the geographical location, with wind and solar also on seasonal and daily changes. Geothermal energy is independent from temporal changes but it is not easily available in each region of the planet, depending on the geological setting. For Sudan the geology offers some evidence of potential geothermal systems and relate energy sources.

1.1 Literature review

1.1.1 Geothermal energy

Geothermal energy is classified as a renewable energy source, which means that its availability is unaffected by a lack of resources or the rising price of fossil fuels and already was harnessed around the world. Higher geothermal gradients are frequently located in active volcanic regions and extensional-shearing tectonic environments where the crustal thickness is less than average [1]. However, because the Earth's temperature increases with depth, geothermal resources can occur everywhere depending on depth, but they may be commercially and/or technically not feasible. The geothermal fluid contains energy in the form of hot water, which can be in the liquid phase, vapor phase, or a mixture of both. The fluid is usually found at a depth of more than 1,000 m below the Earth's surface. The energy for heating up the hot water comes from radioactive decay energy in the earth's core, where temperatures can reach 6,650 °C and moves to the Earth's surface via convection and conduction [2].

The availability of energy is a crucial factor for any society's development. Nowadays, a significant portion of the energy is generated by the combustion of organic fuels to generate electricity. Organic fuels are not widely available in order to use as a source. For example, Indonesia reserve is expected to terminate in 75 years, and 33 years of natural gas reserves [3]. These figures undoubtedly will change over time based on the energy demands. The energy demand is likely to rise over time. Between the 1990s and 2050s, energy consumption could rise over to 275 % of 1990s demand [4].

The energy flowed from these activities is estimated to be up to 42 million MW. Due to the declining of the oil reserves and the discussion of the climate change issue, which aims to minimize the number of greenhouse gases emitted to the atmosphere. Geothermal fuel sources when compared to these fuel source are not emitting greenhouse gases [5]. More efforts have been initiated to explore and develop geothermal resources. In 2014 energy generated from geothermal resources low and medium temperature rise by 17% from 2010 approached 12.5 GW. [6]. Figure 1 explains the progression of geothermal technology in the last 15 years. The study exhibited increasing production from 2010 to 2014 and expected the future scenario, which might be 140 GW by 2050. Moreover, geothermal exploitation is expected to encompass 8.3% of the world's power production and support 17% of the people, with 40 states producing 100% of their energy from a geothermal source [6].

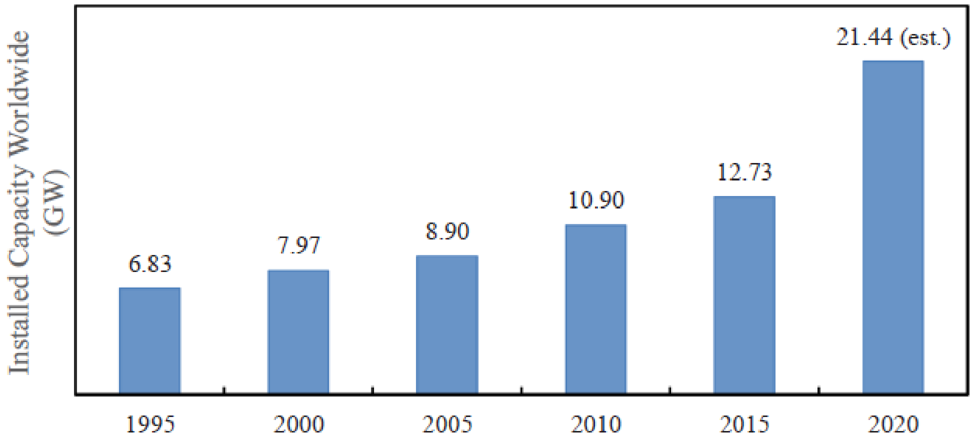


Figure 1 Development of the worldwide installed capacity (in GW) of geothermal power. Value for year 2020 is estimated [6].

A hundred years ago, geothermal energy utilization was known mainly as a heat source for spas and baths. However, harnessing geothermal resources for electricity production started in the twentieth century, with the pilot project in 1904 in Larderello, Italy. In 1913, a 250 kW geothermal power plant proceeded into operation [7]. Geothermal energy applications are classified as direct and indirect exploitations. The harnessing of geothermal energy for any purpose other than electricity generation is referred to as direct use.

Direct applications include industrial processes, agriculture, bathing and balneology, aquaculture, agriculture, swimming, and heat pumps as shown in Figure 2

[8],which call Lindal diagram. According to the Lindal diagram and temperature degree of the fluids, those with temperatures less than 100 °C are primarily used for agricultural and space heating applications, while those with temperatures greater than 100 °C are used for industrial applications. Indirect geothermal category is known by geothermal power plants. High temperature/enthalpy geothermal systems (150 °C to 370 °C) are more suitable for electricity production. Using geothermal resources through drilling wells that penetrate the reservoir layer to produce the hydrothermal fluid and pipe it to the surface is an indirect use of geothermal resources [9].

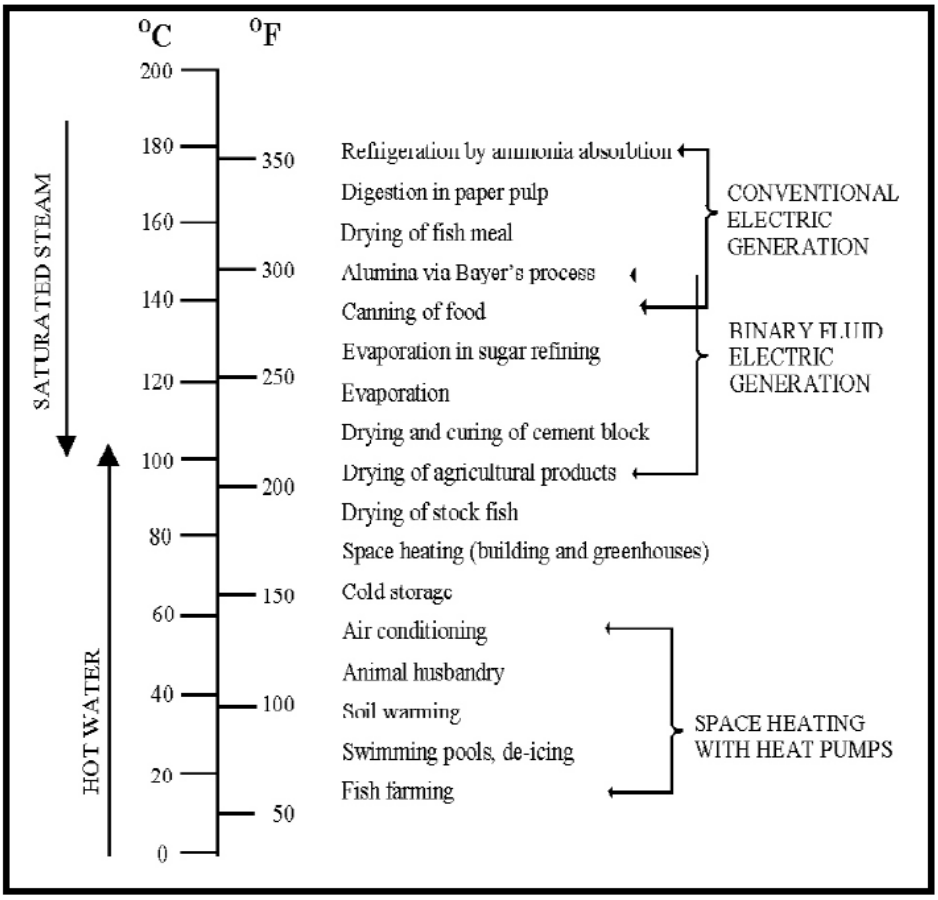


Figure 2 Lindal diagram [8].

Based on the temperature of the geothermal resources or fluids, there are three technologies to produce electricity. Different fluids use to generate electricity that necessitates other technologies of geothermal power plants as following and shown in Figure 3 [9]:

Dry steam plants power plants: To turn steam turbines, this power plant used steam directly from a vapor-dominated reservoir piped from the production wells. This plant is well-developed, with turbine capacities ranging from 35 to 120 MWe and commercially available technology [10].

Flash steam plants: These power plants generate electricity from liquid-dominated systems. The fluid is hot enough to convert a large amount of liquid to steam, which then flows into generator turbines to generate power. The capacity of turbo generator units ranges from 10 to 55 MWe [10].

Binary cycle power plant: Transfers heat from the geothermal fluid to a second liquid, which drives the generator turbine and generates electricity, while geothermal fluid is injected again after the second fluid has been heated. As a heat exchanger machine, the process operates binary cycle power plants. This system is used when the geothermal fluid is not hot enough for efficient flash steam, resulting in the water remaining separated from the steam in conventional flash steam plants [10].

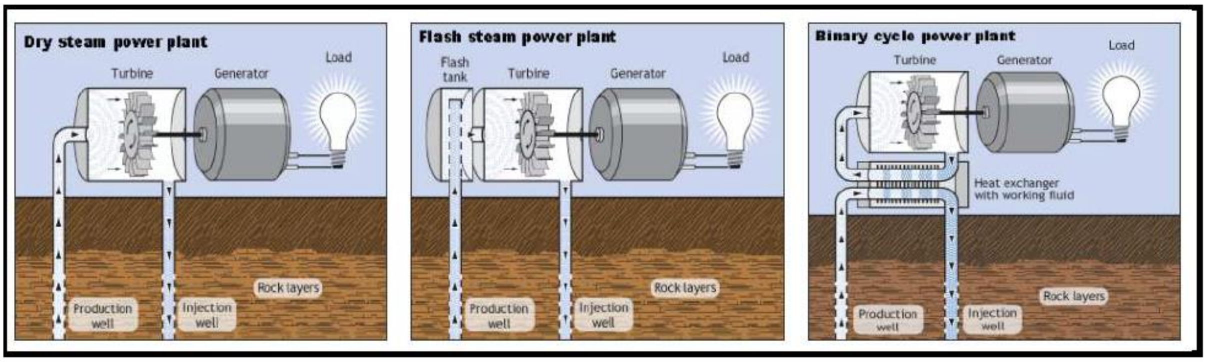


Figure 3 Three main types of geothermal power plants [9].

1.1.2 Geothermal system

Any local geologic environment in which parts of the Earth's thermal energy can be recovered naturally or artificially through circulating the fluids and transported to the harness point is referred to as a geothermal system. In some areas of the Earth's crust, the flow rate and temperature ratio are naturally relatively too low for economic use. Therefore, the flow rate has to be raised to an adequate flow rate/temperature proportion by improving the reservoir characterizations artificially [11].

A geothermal system can be demonstrated systematically by heating the fluid in a restricted space with thermal from the earth's upper crust, then transferring the heat from the thermal source to the heat sink on the Earth's free surface. Geothermal systems generally consist of three components: a heat source, a reservoir, which is characterized by impermeable rocks to prevent hot fluids from escaping to the surface and to keep them under pressure, and the fluid itself, which transports heat from the source or subsurface to the reservoir and/or the surface as shown in Figure 4 [12]. Heat is conducted from magma to the lower impermeable layer, which acts as a heat conductor; the upper impermeable layer acts as a cap or seal rock, trapping heating water in porous and permeable rocks known as "reservoirs." Geothermal energy reservoirs can be economically profitable if they occur at accessible depths and have heat extracted to produce energy.

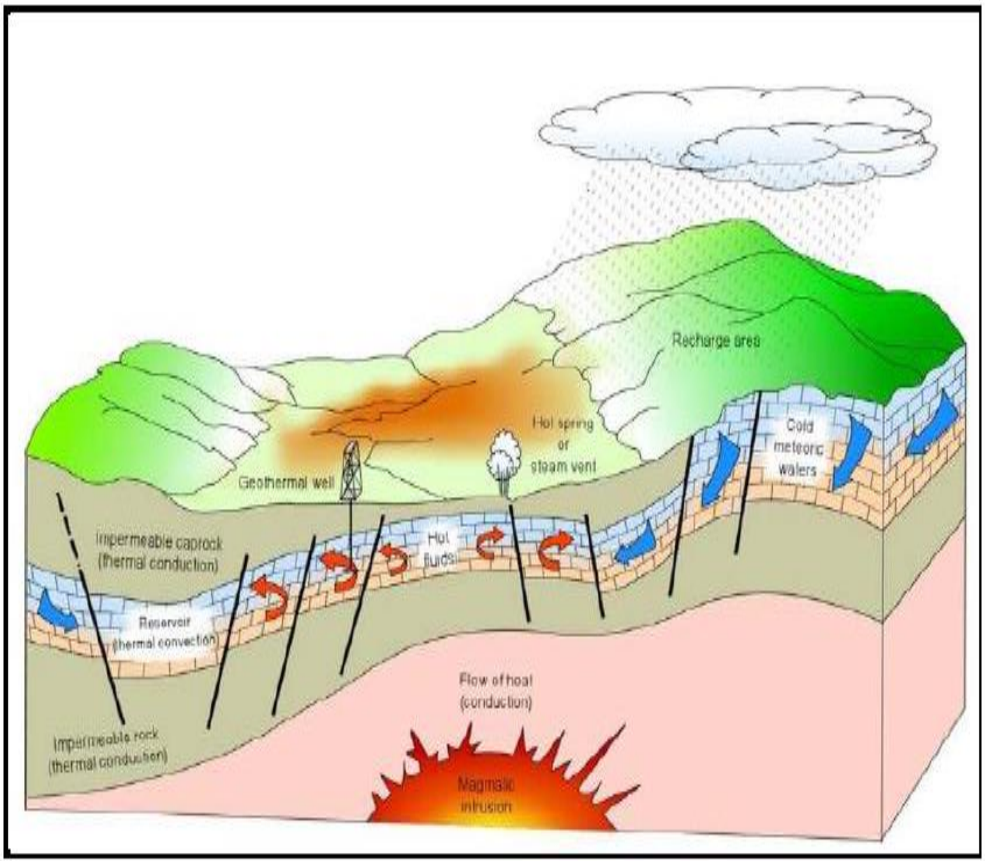


Figure 4 Geothermal system with its elements 12.

Figure 4 explained the geothermal system elements which are related to the volcanic environment from bottom to top. Magmatic body or intrusion is frequently created by continental plate tectonics. A geothermal reservoir is where hydrothermal fluids are confined under high pressure between seal layers (non-porous and impermeable) of rocks and are heated by a magmatic source intrusion below. Freshwater or precipitation runs from recharge zones such as lakes, streams or seas, and stores cool meteoric water that gradually leaks into the ground to lower layers via available structures in the potential areas.

The classification of geothermal resources is based on the heat source, heat transfer type, the temperature of the reservoir, physical state, exploitation, and geological environment. Geothermal systems are divided into four main categories based on the origin of the geological environment as follows: [2]:

Volcanic geothermal systems are linked to volcanic activity in some way. Hot intrusions or magma serve as heat sources in such systems. They are most commonly occurring inside or near volcanic groups such as calderas, with the majority occurring along the plate boundaries but some located in hot spot areas. In volcanic systems, open fractures and fault zones primarily control the flow of water (Figure 5).

For *convective fracture-controlled systems*, the hot crust acts as the heat source at depth, especially in tectonically active areas where the heat flow is above average. In order to extract heat from the potential areas, geothermal water has circulated to great depths (>1 km), primarily through vertical fractures.

Geothermal systems related to sedimentary basins exist in many parts of the world. The existence of these systems is due to the presence of reservoir rocks at great depths (>1 km) and geothermal gradients with values above average (>30 °C/km) (Figure 6).

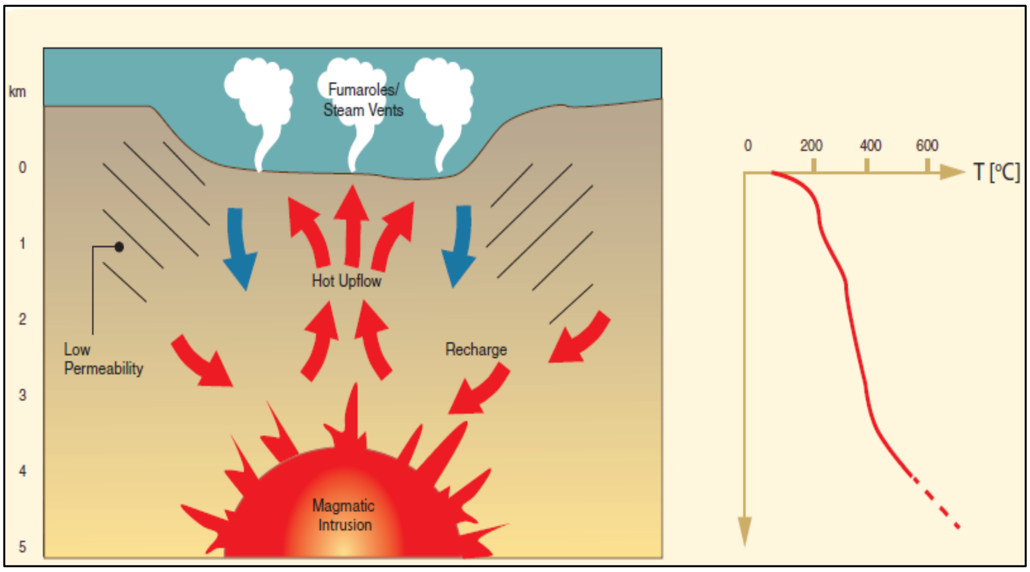


Figure 5 Conceptual model of a high temperature geothermal area, e.g. rift system [2].

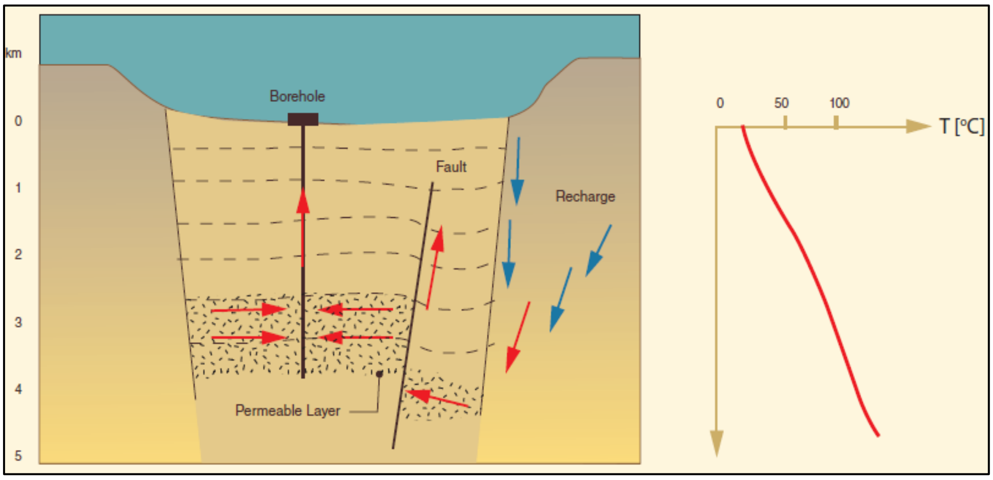


Figure 6 Schematic drawing of a sedimentary basin related geothermal system [2].

Enhanced geothermal systems (EGS) or hot dry rocks (HDR) are volumes of rock with a heat source, whether to be volcanism or abnormally geothermal gradients but have low reservoir characteristics such as permeability, making them unsuitable for conventional use. However, trials have been conducted in several locations to investigate whether hydro-fracturing, also identified as "fracking," can be used to create artificial reservoirs in these systems or improve existing properties. These systems mainly use in production or re-injection duplicates [2].

The "enthalpy" of the geothermal fluids that transport heat from the source of heat to the surface is the most common factor used to categorize geothermal resources. The term "enthalpy" is related to the proportion of temperatures, and it is used to express the heat content (thermal energy) of the carrier fluids, as well as a rough idea of their "value" [13]. Temperature degree is a principal measure of resource quality and, as such, is the primary element of most categorizations systems for identifying and harnessing geothermal energy. United States Geological Survey (USGS) classified geothermal systems into three classes as follows: low-temperature system (90 °C), medium temperature system (90-150 °C), and high-temperature system (>150 °C) [14]. Liquid and steam resources are present in high-temperature systems. Low-temperature systems are entirely liquid-dominated, whereas moderate-temperature systems are almost entirely liquid-dominated. For direct applications all three temperature classes can be used. However, in general moderate- and high-temperature systems are more feasible for electricity generation. Other thermal classification systems have been introduced, with the majority focusing on dividing geothermal resources into three or, more simply, two categorize that define a progression from low to high temperature (or enthalpy) geothermal resources; see also Figure 7 [15]. The temperature/enthalpy limits are set in each case at temperatures thought to be meaningful in either a thermodynamic or an economical exploitation context.

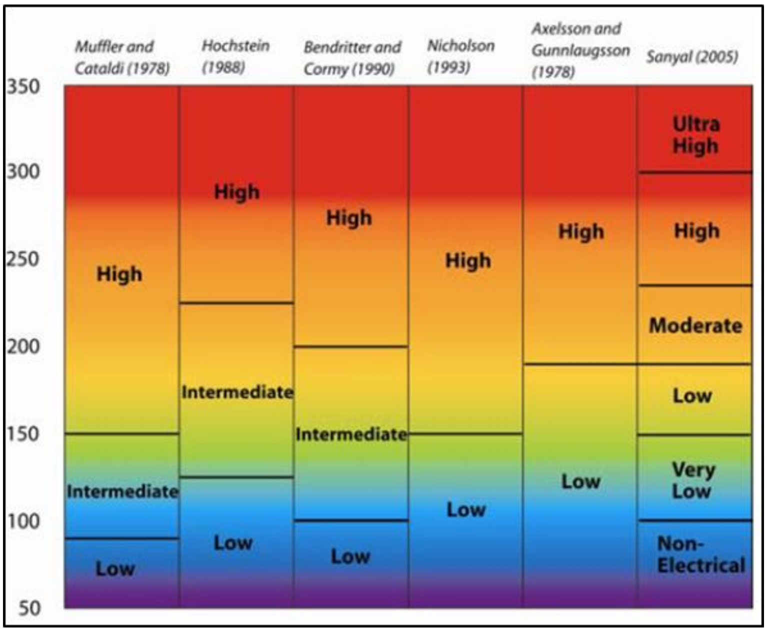


Figure 7 Classifications of geothermal resources according to reservoir temperatures (in °C) [15].

1.1.3 Geological Setting of East-Africa

The East African margin has a complex structure due to multiple stages of rifting with varying stretching directions. The main stage of rifting that resulted in the Indian Ocean's opening continued from 183 to 170 m.y.a. Rifting was caused by the Bouvet hotspot impingement, which decreased the lithosphere sufficiently to allow continental break-up [16]. The East African margin experienced at least five distinct phases with distinct trends as shown in Figure 8 and 9 summarizes the major geological events that impacted the East African margin.

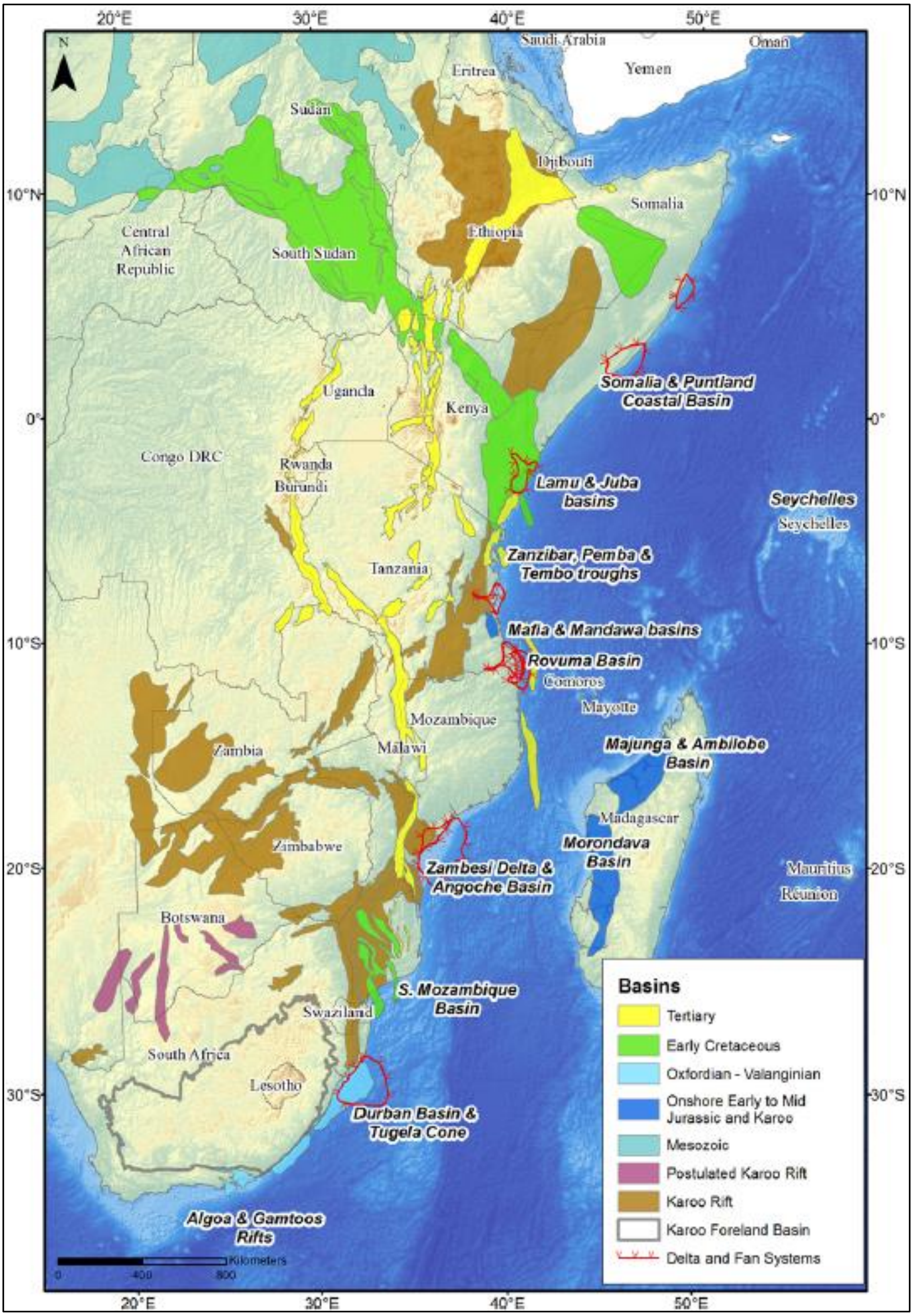


Figure 8 East Africa with its rift basins [16].

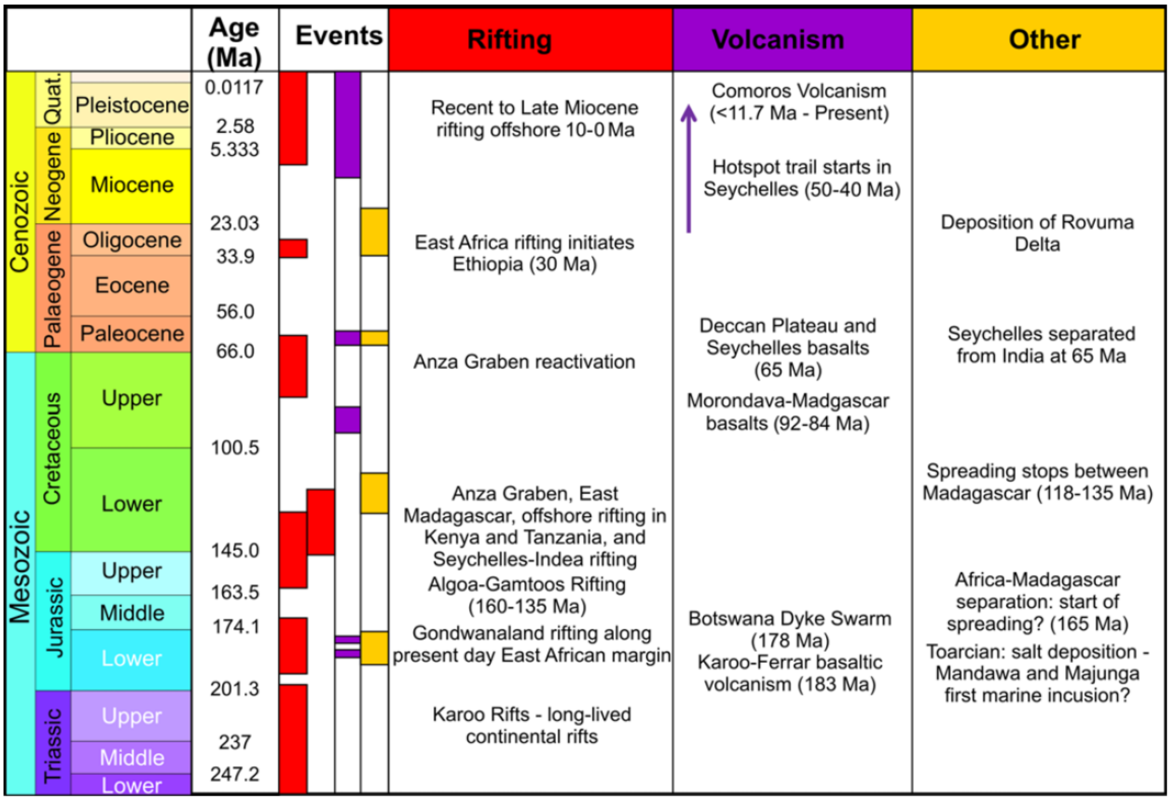


Figure 9 Summary of geological events for East Africa [16].

The East African Rift System (EARS) is a series of rift valleys that stretches over 4,000 km from Beira in Mozambique in the south to the Ethiopian in the north (Afar triangle). The East African Rift System is the continental branch of a global mid-ocean rift system linked to the third branch of the Red Sea-Afar-Red Sea-Gulf of Aden triple intersection. The rift is considered the start of a plate boundary between the Nubian and Somali microplates, and it is connected to the rift systems of the Afar, Red Sea, and the Gulf of Aden Figure 10 [17]. At about 5 °N, the EARS splits into two branches, the Eastern and Western branches. The eastern branch includes the Afar, Ethiopian, Turkana, and Kenya Rifts, whereas the western branch includes the Albert, Kivu, Tanganyika, Rukwa, and Malawi Rifts. Luangwa, Kariba, and Okavango rifts are part of the SW branch.

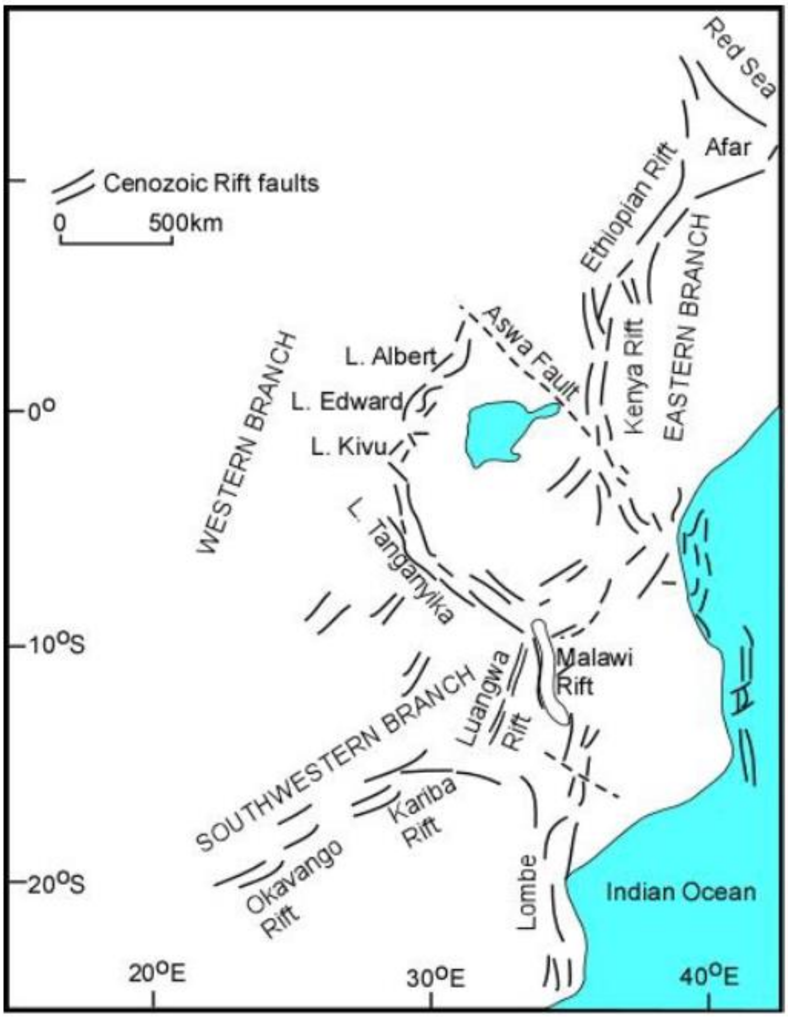


Figure 10 Structural map of the East African Rift System [17].

1.1.4 Geological setting of Sudan

Indeed, the geologic setting influences potential temperature, fluid composition, reservoir attributes, and whether the geothermal system is conductive or convective. [11]. A structural geological understanding, in particular, aids in the interpretation of geophysical data and the identification of favorable drilling locations [18]. The major units are exposed as a crystalline Basement surface of Precambrian era infill with younger consolidated and unconsolidated sedimentary formations ascending to the Recent in the regional geological map of Sudan provided in Figure 11. However, since the beginning of hydrocarbon exploration several decades ago, extensive subsurface data has been collected in the Muglad basin and along to the Red Sea (Offshore and onshore data). The map Figure 12 depicts the major sedimentary basins and their relationship to the basement rocks. These basins are all rift basins, formed by the rifting activity of the Western, Central, and East African Rift Systems [19]. The regional geology of Sudan as shown in the Figure 11, as reported by ACRES, consist of five primary subdivisions, namely as following [20]:

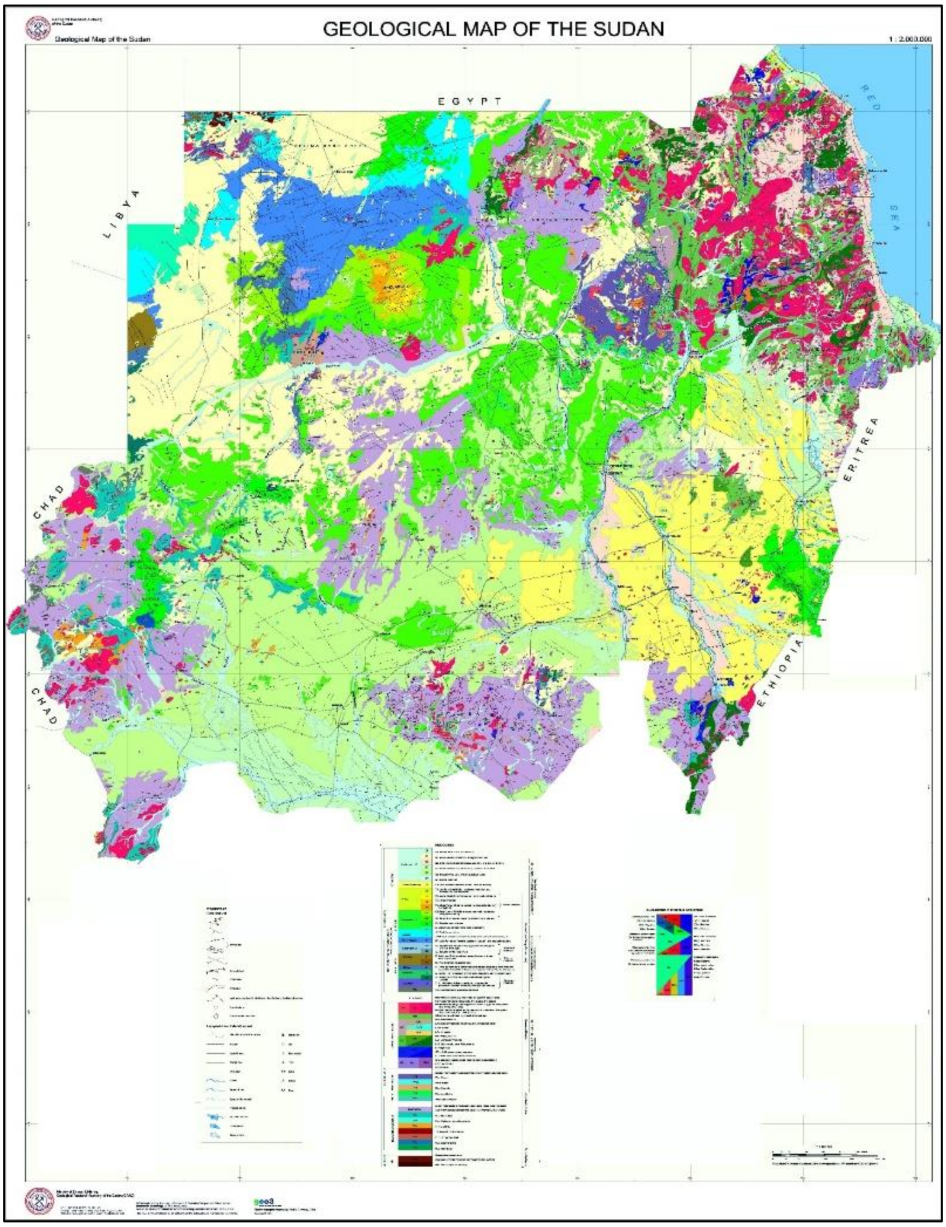


Figure 11 Geological Map of Sudan.

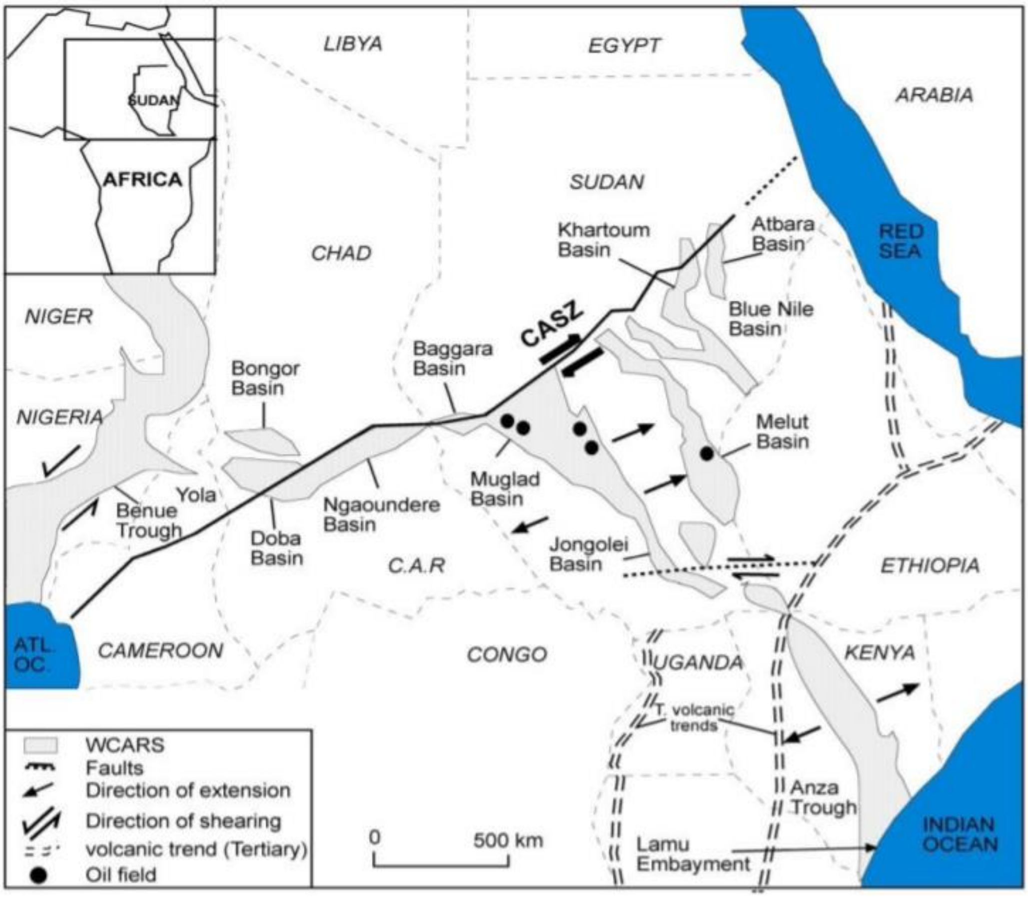


Figure 12 Tectonic model of the West and Central Africa Rift System

Precambrian basement complex (Red & Purple color): Precambrian basement complex rocks are primarily found in Sudan's southwest, central, and northeast regions. In other parts of the country, they are located at depth beneath younger sedimentary and volcanic cover rocks. The basement complex is a metamorphic rock suite composed of granitic gneiss, schist, foliated and unfoliated granite masses, metasedimentary, and metavolcanic sequences. The term is used broadly and is intended to encompass all rocks of the Precambrian age. On the other hand, the basement complex may include younger units, particularly intrusive bodies that have not been identified as belonging to distinctly separate and later events. In general, Archian to upper Proterozoic rocks outcrop in the northeast, near the Red Sea.

Paleozoic and Mesozoic Sedimentary Rocks: In large areas of Sudan's northern half, Paleozoic to Mesozoic sedimentary rocks unconformably overlie the basement complex. These rocks are generally flat and undeformed. The most extensive sedimentary rock unit in this category is the Mesozoic age Nubian sandstone formation (Dark green Color-Cretaceous age). This formation is composed of sandstones with pebble conglomerates, siltstones, and mudstones interbedded. It is found that in a large area north of a line running from Kassala province through Khartoum and the Nuba mountains to Southern Darfur. In some places, the Nubian Sandstone formation rests un-conformably on the basement complex and Paleozoic age strata and the Red Sea littoral group is found along Sudan's Red Sea coast. This group of rocks ranges in age from the Mesozoic to the recent, and it includes shelly and coralline limestone, shales marls, clays, grits, conglomerates, and gypsum beds. It is part of the Red Sea rift basin's extensive sedimentary infilling. Recent exploration work indicates that these rocks contain oil and gas reserves. Undifferentiated Paleozoic sedimentary rocks outcrop near the Egyptian and Chadian borders in northwestern Sudan. These rocks are mostly sandstone, with some siltstone, claystone, and conglomerate.

Tertiary to Quaternary Sedimentary Rocks: Sedimentary rocks fill the vast basins of the Central Sudan Rift zone in the south and southwest Sudan. Much of this area is covered by the Tertiary to Quaternary Age Umm Ruwaba and Gezira formations. These formations are typically covered by windblown sands and fluvial or lacustrine silt/clay soils. Petroleum exploration drilling has revealed that the Umm Rwaba formation is up to 300 m thick and composed of alluvial and lacustrine silt, sand, and gravel. Sedimentary rocks range from the Paleozoic to the Tertiary underlay the Umm Rwaba formation in the rift basins.

Intrusive Igneous Rocks (Light green, yellow and cyan color): A number of granitic intrusions can be found in the Precambrian basement and, in occasionally also in the sedimentary cover overlying it. Granites, granodiorites, diorites, and quartz diorites of late Proterozoic and possibly Paleozoic age are found throughout the country as a medium to large batholiths with associated dykes. Another group of more recent granitic intrusions, known as the 'younger granites,' is thought to be of early Paleozoic to upper Mesozoic age. The 'younger granites' are typically alkaline to Per-alklaine granites, synites, and rarely gabbros that occur primarily as stocks, plugs, and ring dyke complexes.

Volcanic Rocks (Blue color): Tertiary to recent volcanic rocks are found in two areas, which are as follows: a) The Trap series of Ethiopian highland volcanic rocks, which occur along the Sudan-Ethiopian border. b) A line of volcanic centers runs in a northeasterly direction across Sudan from the Jebel Marra complex in western Darfur, through the Meidob Hills, the Bayuda volcanic field near the Nile River, and to the Red Sea Hills. Vail reported that, the trap series in eastern and southeastern Sudan comprises gray-purple, nonvesicular fine-grained lava lower series and more variable upper series of vesicular lavas, tuffs, and basalts [21]. Volcanic activity in Ethiopia near the Sudan border commenced during the early Tertiary and continues through to the present day in some places.

The largest volcanic complex in the north and west Sudan is the Jebel Marra volcanic complex in western Darfur. This area is dominated by the northerly trending 40 km by 150 km Jebel Marra mountain volcanic complex. The mountain and surrounding planes to the east contain numerous volcanic plugs, vents, and scoria cones. The main volcanic feature of the region is the 5 km diameter Deriba crater at the south end of the mountain. Vaile pointed two phases of volcanic activity occurred: new and old series [21]. The old sequence of Tertiary age basalt and basaltic scoria were subsequently intruded by trachyte. The new series is of Pleistocene, and recent age C^{14} data indicates that one flow is 3,000 years old. It consists of basic lava flows emitted from more than 600 m outwards. Air fall pyroclastic also occurred during new series volcanism, the most notable example being in the Deriba Crater. The Jebel Mara volcano is believed to be dormant and has hot springs and fumaroles associated with it. Numerous smaller volcanic centers and lava flows occur on the Precambrian plateau east of the mountain [20].

The Togabo and Meidob Hills make up a volcanic field that extends about 100 to 300 km NE of Jebel Marra. These volcanic rocks comprise of basic to intermediate volcanic flows and dykes that overly penetrate the Nubian sandstone formation. Moreover, Vail reported that rocks are probably late Tertiary to Quaternary in age with more recent activities in some places. [21].

Bayuda volcanic field (BVF) consists of more than 100 relatively small volcanic centers scattered across the Bayuda Desert. A similar volcanic area is located northeast of the Bayuda Desert in the Red Sea Hills. Both volcanic fields contain basaltic lava flows, ash cones, and explosion craters. They appear to postdate the deposition of the Nubian Sandstones formation and, according to Vail, are late Mesozoic to recent in age.

Since the Proterozoic era, a long and complex history of rifting has occurred in Africa. The tectonic progression of Sudan's interior rift basins is linked to Mesozoic-Cenozoic tectonic movements that reactivated the weak lineaments' structures inveterate in the fabric Pan-African mobile belts [22] [23]. During the Mesozoic period (Jurassic-Cretaceous), major rifting phases occurred, resulting in the development of the West and Central African Rift Systems [23]. The movements of rift segments have been inferred as varying along the system's length, with territories of rift-normal extension in many countries such as Kenya, Sudan, Chad, and Libya offset by continental-scale shear zones and linked to many pull-apart basins in Sudan [22].

1.1.5 Geothermal exploration in Eastern Africa

The East African Rift System (EARS) is one of the significant tectonic structures in the world, extending approximately 6,500 km from north to south, from the Dead Sea-Jordan Valley to Mozambique, as shown in Figure 13 [24]. The Great East African Rift, featured in Figure 12, is one of the world's most critical regions, endowed with extraordinary geothermal potential. The East African Rift region could generate approximately 20,000 MWe of energy from geothermal power using current technologies [25].

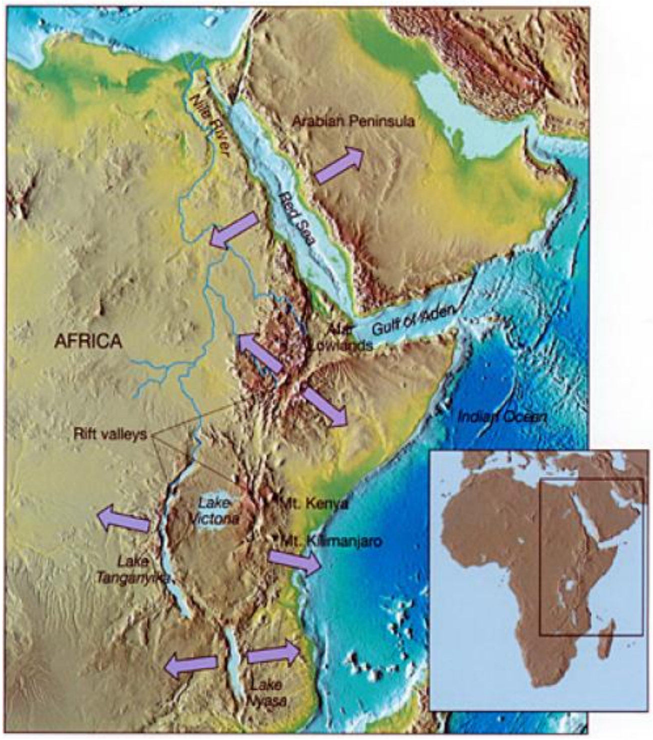


Figure 13 The Great East African Rift System [23].

Kenya is the leading country in this region in terms of geothermal energy use for power generation, followed by Ethiopia [26]. In the East African Rift countries, the total installed electricity capacity from all energy sources is around 20 GWe. Geothermal energy contributes approximately 900 MWe to this, with all existing established geothermal power plants settled in Kenya and Ethiopia [27]. Various levels of geothermal exploration and research have been carried out in Eritrea, Djibouti, Uganda, Tanzania, Malawi, Zambia, and Madagascar, but the potential for grid-connected electrification in eastern African countries such as Ethiopia, Kenya, Tanzania, and Uganda is remarkable [28].

1.1.6 Geothermal exploration in Sudan

Previous surveys highlighted numerous geothermal potential areas in Sudan's north, west, south, east, and northeast. USGS reported that geothermal energy is one of Sudan's energy resources and refers to the increasing temperature of brines and drilled exploration wells along to the red sea to the Rifting process [29]. Another study conducted by Robertson Research's Geothermal Division summarized the potential geological areas: Jebel Marra, Tabago Hills, Meidob Hills and surrounding areas, Atbara Area, Gaderif Area, Red Sea Region, Khartoum Area, and Central Sudan Rifts [30]. ACRES International Limited reviewed Sudan's geothermal potential using previous reports, geological maps, aerial photographs, and site visits to potential geothermal areas of interest.

Finally, four potential areas were discussed and highlighted by ACRES Central Sudan Rift zones, Jebel Marra (volcanic complex and surrounding areas), Bayda Volcanic Field, and Red Sea Coastal Plain [20]. Furthermore, the UNESCO science sector conducted a fact-finding mission on geothermal resources in Sudan to assess the geothermal features of some areas of the country [31]. KEMA prepared a report on strategic renewable energy options in 2009, with funding from the Dutch Ministry of Foreign Affairs, and reported that geothermal energy appears to be available in Sudan [32]. Kenya Electricity Generating Company (KenGen) carried out a geoscientific survey to appraise the geothermal potential of the Bayuda field. The previous work generally appointed the volcanic areas, central Sudan rift zones, and Red Sea coastal plain as a potential geothermal areas as shown in the Figure 14 [20].

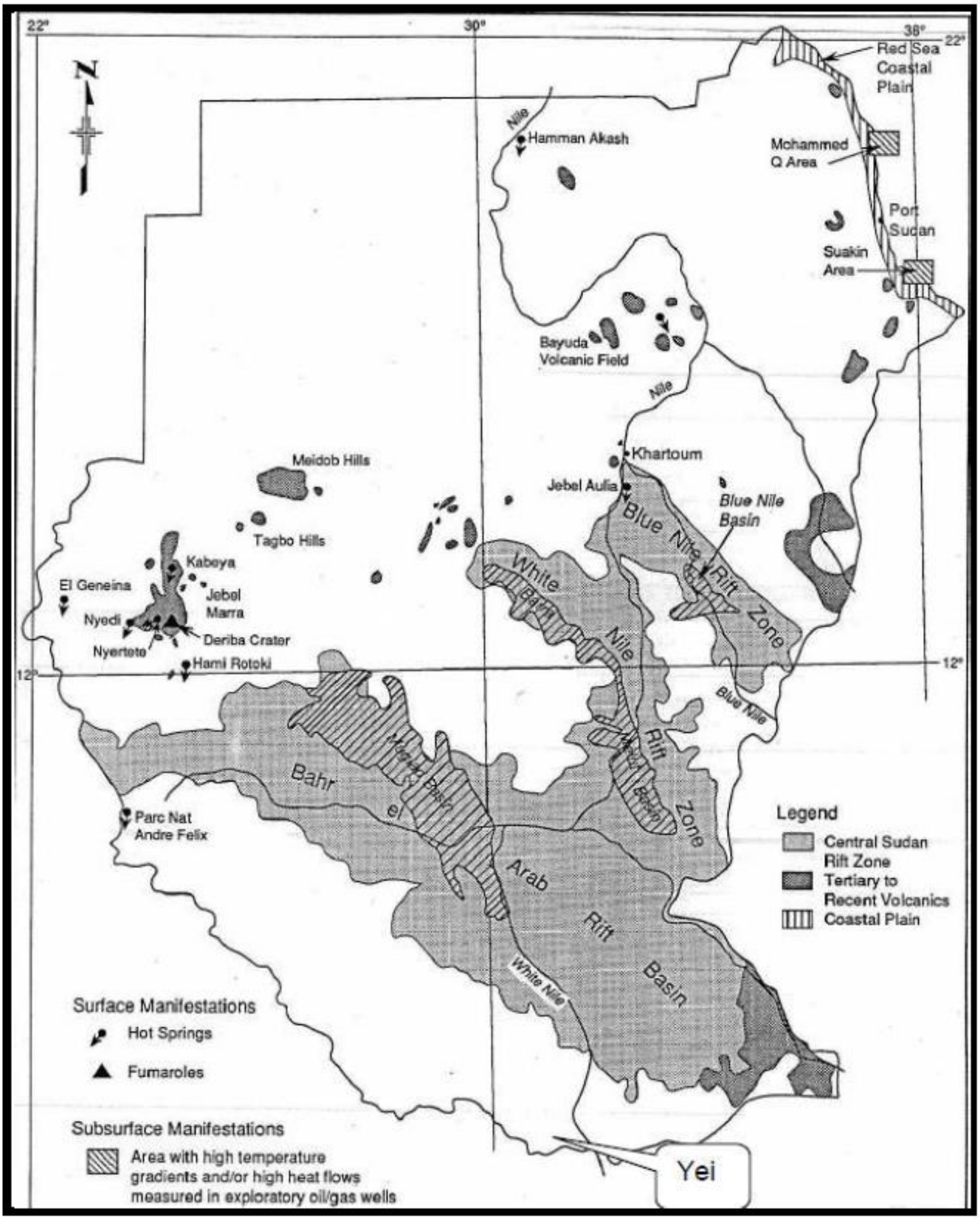


Figure 14 Potential geothermal areas in Sudan [20].

1.1.7 Geothermal development steps

Throughout all phases and stages of development, geothermal development is subject to various risks to varying degrees [31]. Resource risk manifests itself in various ways, including resource availability and size, suitability, sustainability, and utilization issues. The main challenges to the greater harness of geothermal energy for power generation are risk and financing. Like most other renewable energy technologies, geothermal has a high up-front cost and relatively lower running costs than conventional thermal power generation schemes. Figure 15 exhibits a conceptual representation of the various stages of geothermal power development and the associated changes in risk level and typically ordered a range of capital investments [33]. The highest risks in new geothermal schemes are encountered during the early stages of surface survey and exploration drilling (Stages I & II). Getting the financing needed to overcome this geological exploration risk (or resource risk) is frequently regarded as the most difficult challenge [31]. This study presents an assessment approach applied to assess geothermal fields in Sudan to mitigate geothermal resource risks to address early-stage uncertainty and mobilize investments in geothermal exploration. The work was done to help decision-makers make informed decisions about implementing the most practical support mechanisms to develop geothermal energy utilization and diversify the country's energy.

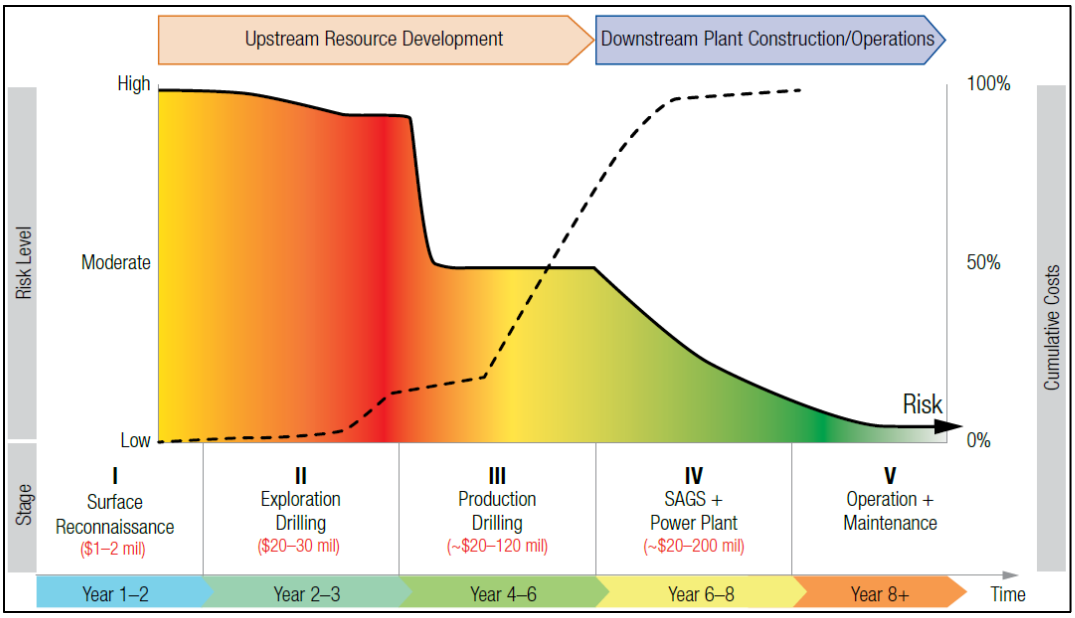


Figure 15 Conceptual representation of risks and costs during the different stage of a geothermal development.

1.2. Objectives

The main objective of this research work is to assess and prioritize the recommended potential geothermal resource areas of Sudan (PGRAS) for further exploration as a result of the developing geothermal technology. Therefore, this study provides an assessment and a ranking for all potential areas in Sudan based on the positive attitude factors method to support any decision-making process for further geothermal exploration and to delineate missing data required to be known before deciding on any exploration. Ultimately, this will mitigate the financial risk and uncertainties and increase the chance of success for the further exploration activities of geothermal resources. Advanced research funds and further investments therefore can be focused on specific sites.

Synchronously, a global COVID-19 pandemic is threatening to have long-term social, economic, and political consequences, particularly in a country like Sudan, which is already burdened by extreme poverty and chronic conflict. Measures of developing geothermal resources will contribute to sustainable development and address the development challenges mentioned above.

CHAPTER 2
METHODOLOGY

2. Assessment of geothermal resources

The assessment of natural resources can be done qualitatively as well as quantitatively; however, the latter one is preferred as numbers and values are easier to be comprehended in economic and financial models and planning. The same holds for the geothermal resources as here many of the primary parameters are descriptive in nature. Here the positive attitude factors design is used to transfer descriptive geoscientific and related information into values and numbers.

2.1 Assessment using positive attitude factors design

The assessment of geothermal resources has become standard practice, and the geothermal industry is assessing a geothermal system's potential generation capacity [1]. It is critical in determining the amount of valuable thermal energy that can be generated and used for electricity generation or direct use applications. The assessment is also employed as a framework for sustainably developing a geothermal potential. It gives stakeholders, companies carrying out exploration activities, resource developers, and government agencies confidence when starting a new geothermal scheme. Several methodologies for evaluating resources have been developed and implemented both analytical and numerical solutions over the years. The initial approaches were primarily qualitative. Existing geothermal provinces were practiced as analogue fields to evaluate the potential economic value of geothermal prospects [34].

Positive attitude factors design is a method used to assess the geothermal sites in Southern Thailand. The assessment was developed to define factors that will allow all sites to be assessed consistently, and subsequently allowing resource sites to be ranked [35]. Ultimately the *positive attitude factors* design method will be used to rank the promising area for further exploration. This method can help collect geothermal site data and provide continuously updated estimates, allowing advanced surveys, which waste time and money, to be avoided. The positive attitude factors method supports any decision-making process for further geothermal exploration and helping to figure out the required data in order to establish proper assessment before taking any decision regarding the exploration. As shown in Figure 16 in order to assess the potential of specific geothermal, reliable evaluation has to be carry on based on reservoir characteristics, heat source and resource temperature. Due to gab of required data

Positive attitude factors method initiated to collaborate common geothermal field parameters [35].

Positive attitude factors method is described as an analytical method established to evaluate the geothermal fields based on the weight of the common factors. Positive attitude factors consist of four broad factors: previous exploration, land use, reservoir, and market factors. These factors were given scores from 3 (highest) to 0 (lowest), which refers to the characterization of each factor. Ranking criteria and weights of each factor refer to the weight in the assessment. Ultimately the total scores of all factors will define the ranking/prioritization and potentiality level of development for each field.

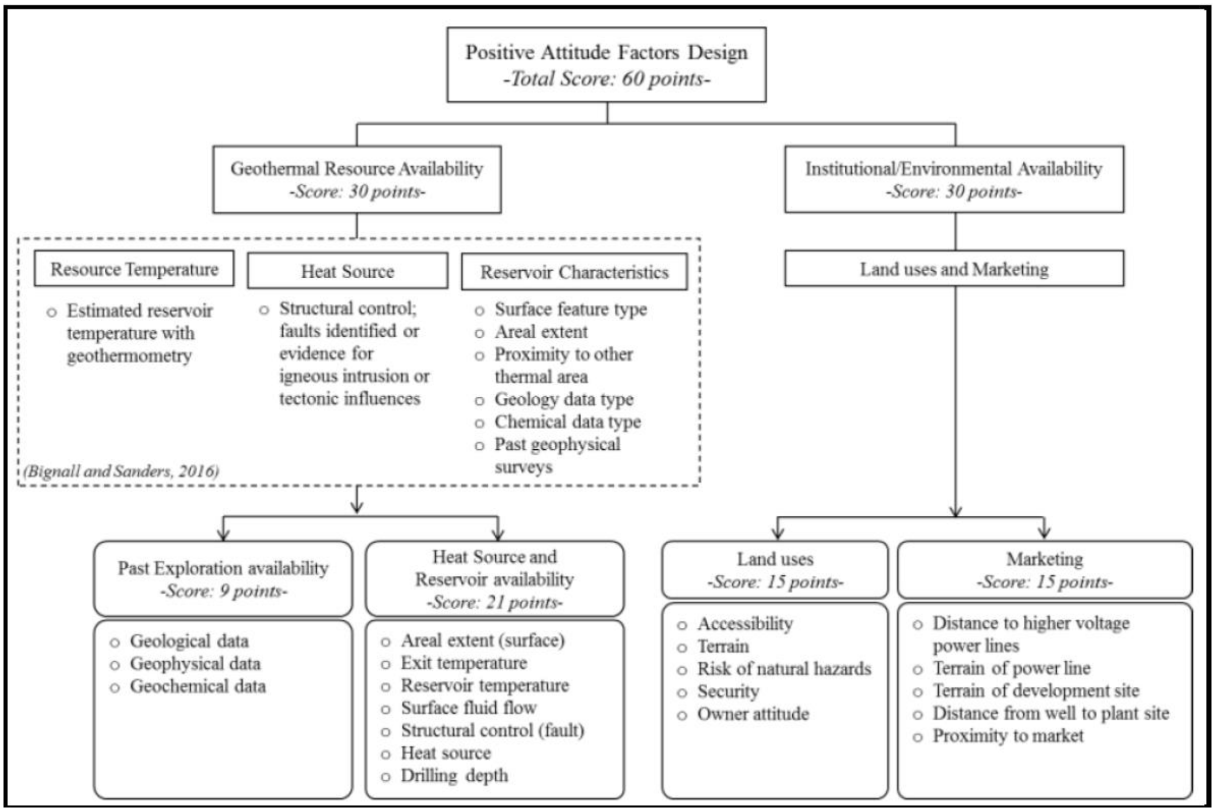


Figure 16 Positive attitude factors design method for geothermal sites ranking [34].

2.1.1 Factors of land use availability

This factor, as shown in Figure 16 is including five parameters, accessibility, terrain, risk of natural hazards, security, and owner attitude factors. Each of them was divided into three levels and given scores based on the characterization of each factor (Figure 17) [35]:

(1) Accessibility: Ability to access the potential areas weather for exploration or

development geothermal resources. It was classified and rated as (3) for main road or highway, (2) paved road, and (1) rural non-paved road.

(2) Terrain factor: Physical features surrounding the potential areas of geothermal resource. The terrain was classified and rated as (3) for flat or nearly flat, (2) hilly, forest, or mangrove, and (1) mountainous.

(3) Risk of natural hazards factors: Natural hazards include atmospheric, hydrologic (e.g., flooding), geologic (particularly seismic and volcanic), and wildfire phenomena around the potential areas. Based on frequency, the events were divided into three categories and rated as follows: (3) never, (2) non-frequent events, and (1) more frequent events.

(4) Security factors: Security factors are the frequency of incidents which effect directly to the any exploration or development operations around the potential areas. It was classified and rated as follows: (3) no security incidents, (2) occasional security incidents, and (1) monthly security incidents.

(5) Owner attitude: The owner people or villages attitude nearby of potential areas was divided and rated as follows: (3) strongly agree, (2) agree, and (1) indifferent.

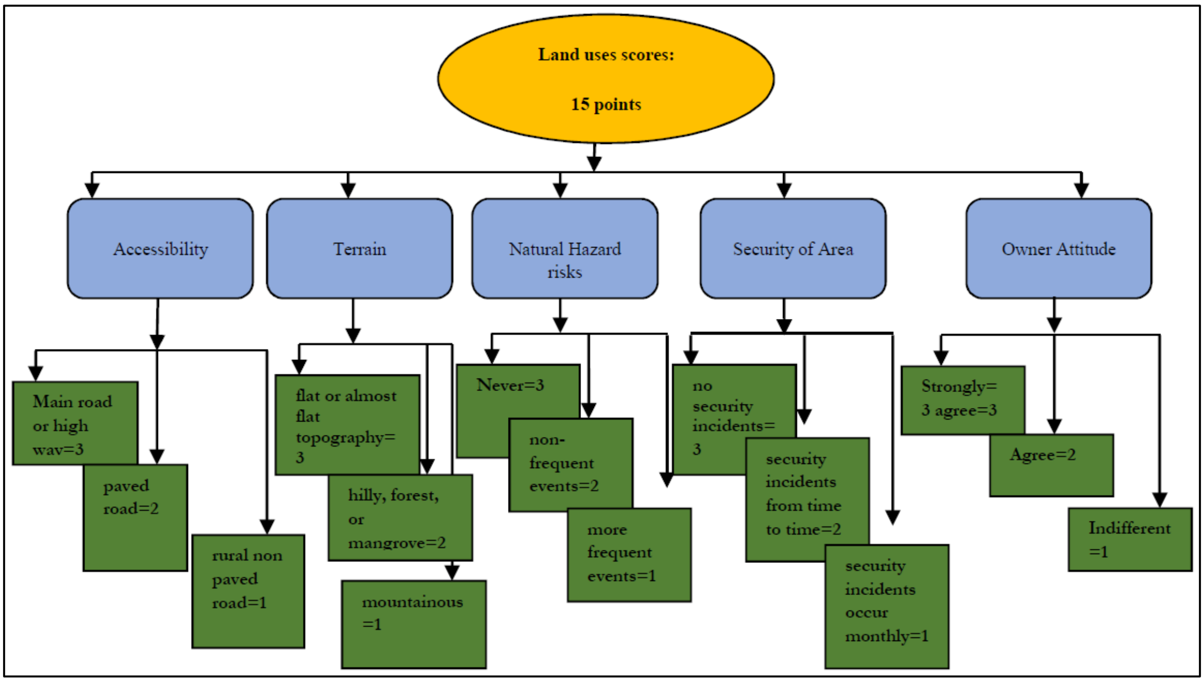


Figure 17 Land uses factors score.

2.1.2 Factors of past exploration availability

This factor includes geological, geophysical and geochemical data and as the previous one rated into three categories based on which set of data is available (Figure 18) [35].

This factor includes (Geological, geophysical and geochemical data) as the previous one rated into three categories based on which set of data is available (Figure 17).

(1) Geological factors: Geological factors are referring to the level of any geological survey or exploration studies which have been done in the potential areas. As a result, it was divided into three categories and rated as follows: (3) for complete data (surface, shallow, and deep), (2) for nearly complete data (surface, shallow, or deeper), (1) for incomplete, and (0) for no data available diffraction data, or others constitute the shallow information whereas deeper information comes from geological modeling.

(2) Geophysical factors: Geophysical factors it means the geophysical available data and which method has been implemented. It was classified and rated based on the depth of investigation obtained using the methods described below: (3) for complete data (surface, shallow, and deeper), (2) for nearly complete data (surface, shallow, or deeper), (1) for incomplete data, and (0) for no data. Geographic information system data or maps define Surface information data, whereas shallow information contains electrical resistivity data. Deeper information includes gravity, magnetotelluric (MT) surveys and seismic survey.

(3) Geochemical factors: Geochemical factors are categorized and rated based on the isotope data availability as follows: (3) for complete isotope data, (2) for cation/anion composition geothermometer data, and (1) for no data.

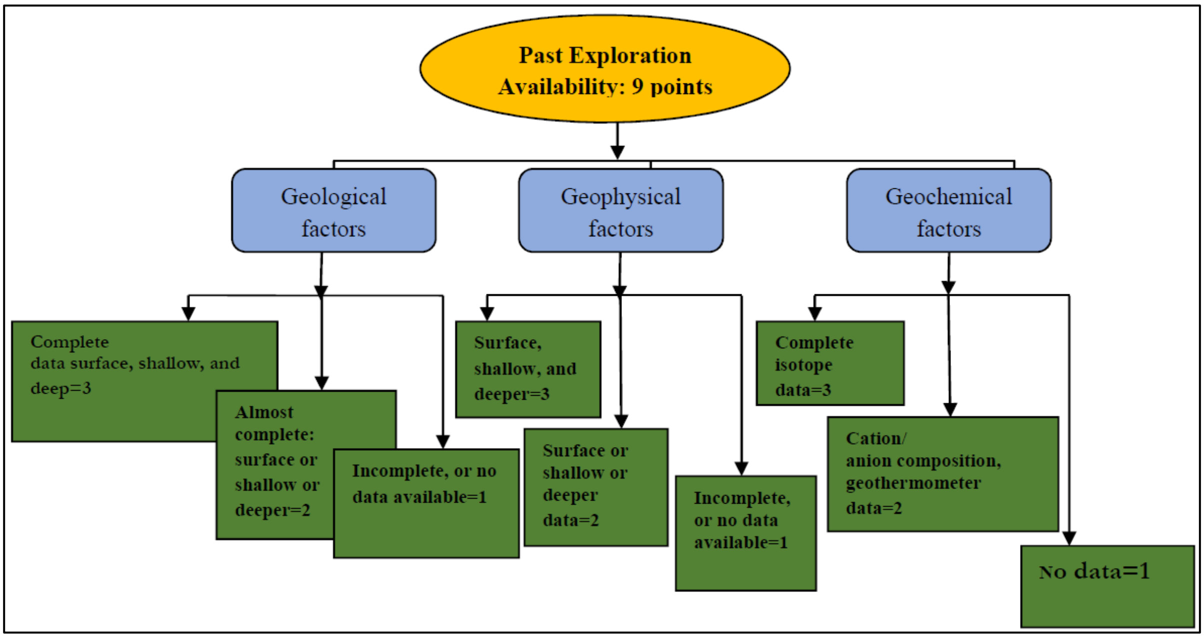


Figure 18 Past exploration availability factors score.

2.1.3 Factors of reservoir availability

Seven parameters define this include areal extension, exit temperatures, shallow reservoir temperature, surface fluid flow, structural control, heat source, and drilling depths, [35], as shown in Figure 19.

(1) Areal extension: For large-surface manifestation (>1 km^2) areal extension (surface) was rated (3), rated (2) for medium-surface manifestation (>0.5 km^2 to 1 km^2), rated (1) for small-surface manifestation (<0.5 km^2) and (0) for no data.

(2) Exit temperatures: Exit temperatures have been rated (3) for high surface discharge temperatures (≥80 °C), rated (2) for intermediate-surface discharge (>70 °C to <80 °C), for low-surface discharge temperatures (60 °C to <70 °C) rated (1) and (0) for no data.

(3) Shallow reservoir temperature: Shallow reservoir temperature factors are rated as (3) for high-temperature systems (150 °C), (2) for intermediate-temperature systems (150 °C to 90 °C), (1) for low-temperature systems (90 °C), and (0) for no data.

(4) Surface fluid flow factors: Surface fluid flow factors rated (3) for higher flow rates (≥1 L/s), (2) for lower flow rates (>0.1 L/s to <1 L/s), and (1) for no data.

(5) Structural control: Structural control rated (3) for main large faults or fractures, (2) for subordinate faults or fractures, (1) for no faults or fractures, and (0) for no data.

(6) Heat source: Heat source rated (3) for only granite settings, (2) for granite and sedimentary/metamorphic settings, (1) for only sedimentary/metamorphic settings,

and (0) for no data.

(7) Drilling depth: Drilling depth rated (3) for more than 300 meters, (2) for over 150 meters, but not exceeding 300 meters, (1) for less than 150 meters, and (0) for virgin fields or no data.

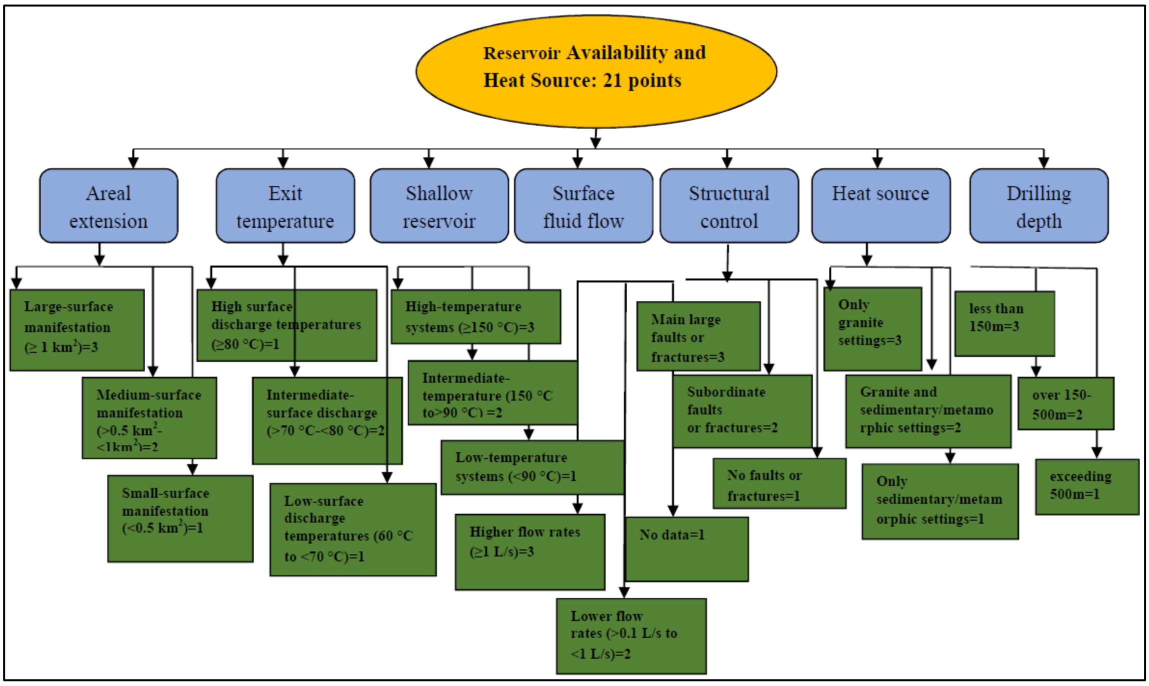


Figure 19 Reservoir availability factors score.

2.1.4 Factors of marketing availability

Market availability includes the following factors, distance to higher voltage power lines, terrain of power line corridor, terrain of the development site, distance from well to plant site, and proximity to market whether it is close, over 500-1,000 m, or exceeding 1,000 m as shown in Figure 20.

(1) Distance to higher voltage power lines: Distance to higher voltage power lines is rated (3) for less than 5 km, (2) for more than 10 km but less than 15 km, and (1) for more than 15 km.

(2) Terrain of power line: The terrain of the power line corridor is rated (3) for flat or nearly flat topography, (2) for hilly, forest, or mangrove terrain, and (1) for mountainous terrain.

(3) Terrain of development site: The development site's terrain is rated as (3) for flat or nearly flat topography, (2) for hilly, forest, or mangrove terrain, and (1) for mountainous terrain.

(4) Distance from well to plant site: Distance from well to plant site rated (3) if

it was less than 200 meters, (2) if it is more than 200 meters but did not exceed 500 meters, (1) if it was more than 500 meters, and (0) if it is unknown.

(5) Proximity to market or production areas: Proximity to market factors rated (3) for close, less than 20 km, (2) for moderate, over 20 km, but not exceeding 50 km, (1) for far-exceeding 50 km, and (0) for unknown distance.

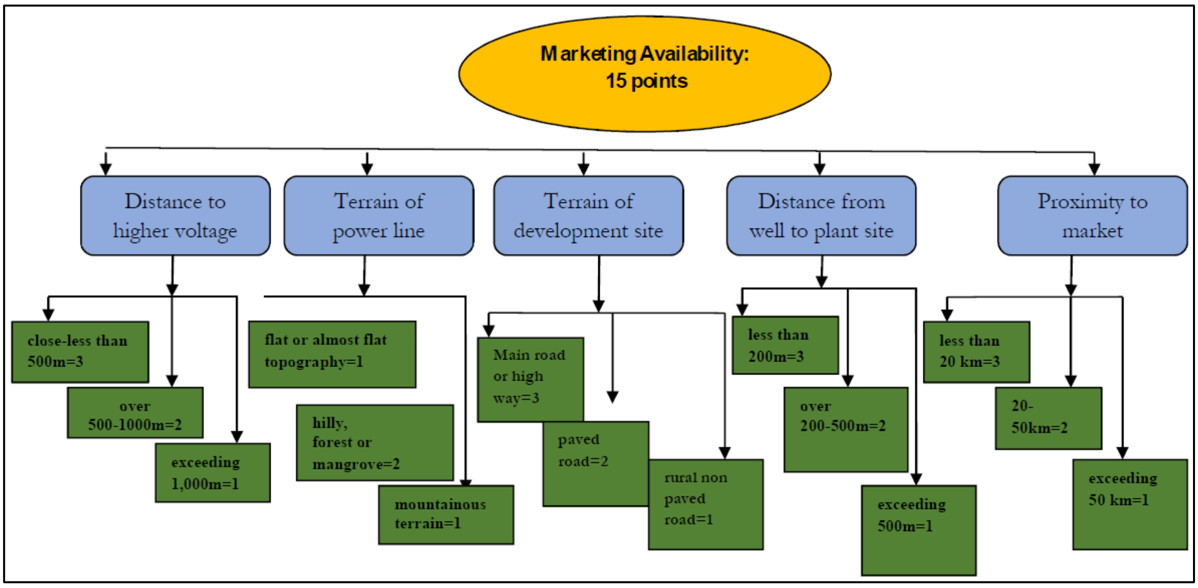


Figure 20 Marketing availability factors scores.

2.2 Ranking

Based on reports, geological maps, aerial photographs, and site visits to potential areas of geothermal interest, the ACRES project evaluates Sudan's geothermal potential. As a result, It identifies four potential geothermal areas: Central Sudan Rift Zones (Muglad Basin), Jebel Marra (volcanic complex and surrounding areas), Bayda Volcanic Field, and Red Sea Coastal Plain [20]. Many hot springs and fumaroles in Jebel Marra were discovered and mapped as part of the paleo-climatic study [36][37]. High heat flows were reported from oil wells drilled in the Muglad basin, representing a stage of Sudan's central rift to explore, develop, and produce oil [20]. Red Sea Coastal area also high heat flows were reported from oil exploration wells drilled offshore and onshore [38]. KenGen (Kenya Electricity Generating Company) conducted a geoscientific survey to assess the geothermal potential of the Bayuda field [39]. The proposed ranking of the potential areas in the Republic of Sudan is consists of two stages as follows:

2.2.1 Numerical Scoring Assessment

A dependent variable for each factor mentioned above was chosen in the assessment, providing a relative rate for each resource field to be defined Figure 15. This corresponding rate is based on the assessment and Ranking of Hot Springs Sites applied in Southern Thailand [35]. Resource rates for all potential areas' factors were assigned and figured out the total based on the available information.

2.2.2 Final Ranking

This stage indicates the significance of all four fractions rather than the sum of all positive attitude factors [2]. The percentage and cutoff of each fractional score for the exploration and land factors were set at 80% at this stage, while the cutoff for the marketing and reservoir factors was set at 55% due to a lack of data. Cut-off values were introduced in order to ensure that a specific region receives a high priority with very high to full scores in one or two fields only [2]. Initially a cut off value of 80% was introduced to all four fractions; but as mentioned above, in the marketing and reservoir fraction data very not sufficient to reach 80%; therefore, the cut off value for these two fractions in this study was lowered to a reasonable value of 55%. When the values exceeded the cutoff, the field received a positive mark, and all marks were added to determine the final ranking [2]. At the end of this stage, sites were ranked and planned the future geothermal exploration activities that might carry on as illustrated in Figure 21.

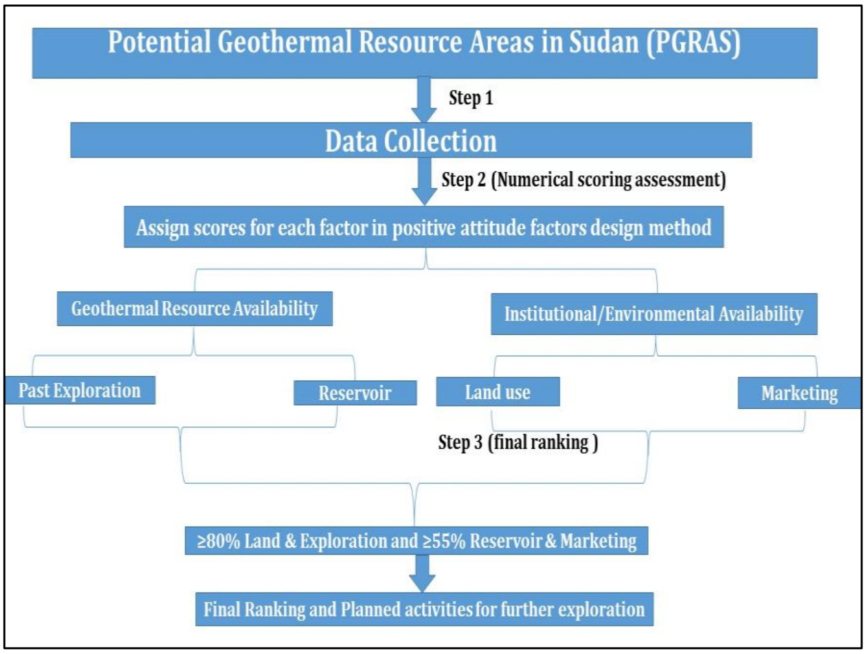


Figure 21 Work flow of this study.

2.3 Scope of the study and data

Using a positive attitude factors design approach, the study assessed and/or ranked potential geothermal areas and defined the future exploration activities to develop the geothermal resource of Sudan's Republic. Data on assessment and ranking were categorized and analyzed from previous studies, reports, papers in related academic journals, and documents available on the Internet, among other sources.

CHAPTER 3
RESULTS

3. Assessment of geothermal potential areas in Sudan

An initial geological assessment outlined in Section 1.1.6 has shown that Sudan can be divided into four areas to be assessed independently, with 1) Jebel Marra Mountains, 2) Bayuda Volcanic Fields, 3) Red Sea area, and 4) Muglad Rift Basin area [20]. In the following the detailed assessment results of all four areas are shown.

3.1 Jebel Marra Mountains

3.1.1 Land use availability factors

(1) Accessibility factor

Sudan's road network serves as a major conduit for transportation, as well as it provides economic and social benefits Figure 22 [40]. According to a field survey conducted in 2017, 43% are in good condition, 33% are in fair condition, 24% of the roads are in poor condition, and the major problems and obstacles observed are cracking and raveling failures of the road surface [41]. The Jebel Marra is divided into three states: Nyala in Southeast Darfur, El Fasher in North Darfur, and West Darfur in West Darfur (Genena), with the highest point is approximately 130 kilometers from El Fashir town. In 2001 UNESCO sent a mission to conduct research on geothermal energy sources throughout the country. Inaccessibility was one of the main challenges the UNESCO mission faced when exploring the entire area of Jebel Marra [20]. There is only one major road leading to the area, passed by Nyala and crossing Kass until reach Nertiti and further to Zalingei, rail road across Nyala to Aljunaynah as well. Accessibility factor score here is (1).

(2) Terrain factors

Jebel Marra is a 13,000 km^2 volcanic massif that stretches for 140 km from north to south and is 80 km from east to west. [37]. Monthly temperatures mean in the Jebel Marra area ranged from 23 to 26 °C at all three stations. In addition, the mean annual rainfall was 692.43 mm at Wadi Salih and ranging from 520 mm at Zalingei to 672.02 mm at Nerttiti [42]. Jebel Marra Mountains has sandy plains, clay plains, wadis and slopes [42]. These larger areas are dominated by sand dunes and a drainage system as shown in Figure 23.

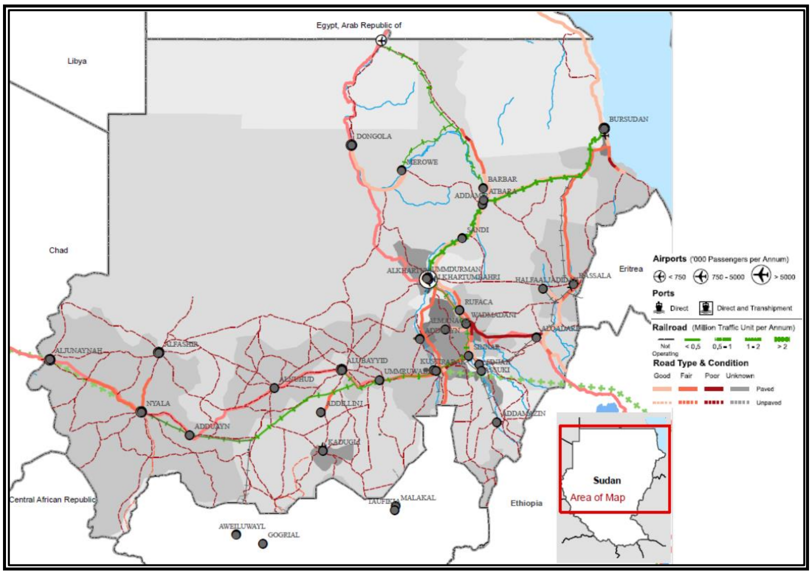


Figure 22 National and regional transport network in all parts of Sudan.

The Jebel Marra mountains comprise of a central non-active volcano cone within a caldera that contains a deep crater lake and that occupies a former vent of the volcano, while the lowest part of the sloping floor to the east contained a shallow lake nearly 2.5 km long [36]. A crater and number of hot springs were observed in Jebel Marra area [43][20][31][36]. Jebel Marra is a mountainous area with an elevation of up to 3,042 meters and is made up of 2,000 meters thick layers of lava and pyroclastic rock layers [37]. An UNESCO team reported that Jebel Marra has difficult terrain, which make some areas only accessible on foot [20]. Terrain factor score here is (1).

(3) Risk of natural hazards factors

Jebel Marra is in Darfur, which is part of the Sahel, a belt of semi-arid to semi-humid grasslands and wooded savannas that borders the Saharan desert. According to the Global Humanitarian Forum in 2009, the Sahel is one of the most physically vulnerable areas to climate change due to its proneness to drought and its inhabitants' strong reliance on rain-fed farming and herding [44]. Jebel Marra is a fire-prone area that is subjected to severe wildfires on an annual basis (with an increasing trend), but all of the fires in the area are man-made, with no evidence of natural fire ignition. The most common causes of fire in Jebel Marra are honey collection, agricultural land cleaning, and tribal conflicts [45]. Risk of natural hazards factors score: (2).

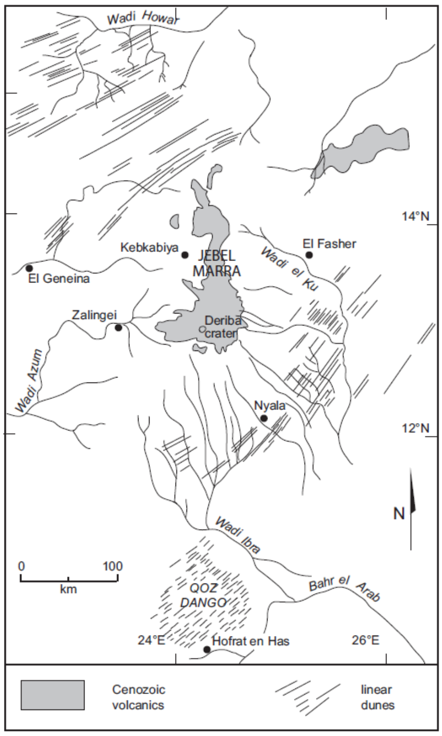


Figure 23 Sand dunes and drainage systems in the Jebel Marra area [40].

(4) Security factors

Since 2002, violence has persisted in Darfur's Jebel Marra area between government forces and the Sudan Liberation Movement. Security situation of Jebel Marra from 1 March to 31 May 2020, United Nations African Mission In Darfur (UNAMID) reported 48 incidents of armed conflict, resulting in 115 deaths, compared to 37 incidents and 34 deaths in the previous year [46]. Since 2003 Darfur has been plagued by armed conflicts between the Sudanese government and opposition groups. The conflict has created a high level of violence directed mostly at civilians. Root causes of the conflict are numerous, like underdevelopment, marginalization by the government, low resource availability, and consequences of previous conflicts [47]. Security factor score: (1).

(5) Owner attitude

Jebel Marra is one of Sudan's most biodiverse and scenically significant areas. The main source of income for the locals is the cultivation of pineapples, mangoes, guavas, oranges, bananas, grapes, sugar cane, papayas, and other fruits and vegetables. However, because of the lack of proper transportation infrastructure, the majority of the products are essentially sold where they are found [20]. The region has a high number of livestock, which is make Jebel Marra one of the riches area. UNESCO team reported that local people they welcome any international assistance from organizations, to develop activities in the region [20]. Owner attitude score: (3).

3.1.2 Past exploration availability factors

(1) Geological factors

An area of Jebel Marra covers by volcanic massif around 13,000 km^2, and the wide is up to 80 km from east to west and 140 km long from north to south It attains an elevation of 3,042 m and is composed of some 2,000 m of lavas and pyroclastic rocks [37]. The occurrence of volcanic fields associated with tectonic activity along to the margin of plate tectonic or subduction zone [48]. Jebel Marra volcano is unusual because it lies close to the center of the African lithospheric plate where there is no subduction zone or edge of tectonic plates. It is an intraplate alkalic volcanic complex positioned in the African lithosphere, possibly at a triple junction [49][50]. Jebel Marra Mountains are assumed to be located at a likely triple junction in the East African lithosphere. The triple junction is made up of three arms: 1. The Abu Gabra rift to the southeast of Jebel Marra; 2. The Ngaoundere lineament, which represents a Pan-African dextral shear zone; and 3. The volcanic fields of Hoggar in Algeria and Tibesti in Chad, as shown in Figure 24 [51].

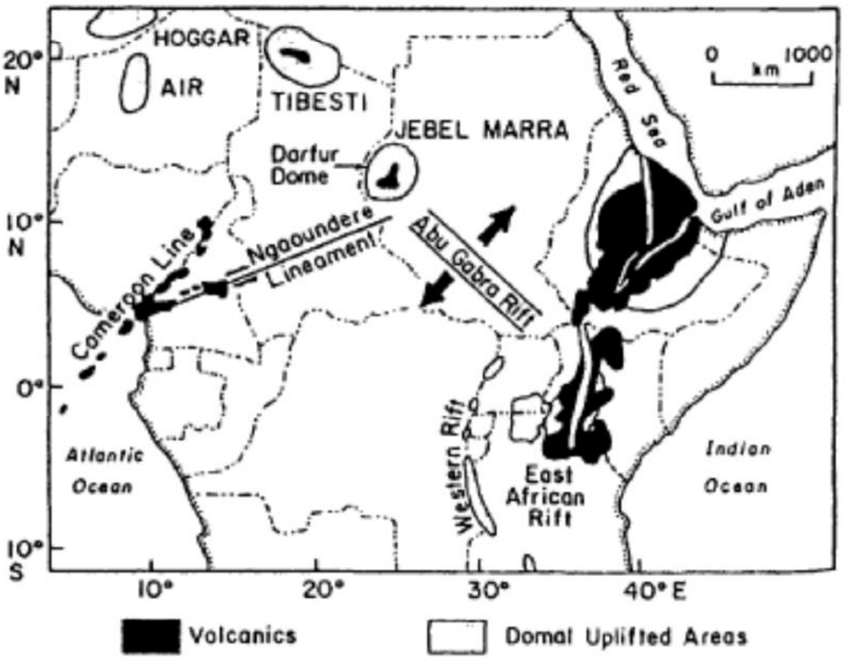


Figure 24 Location of Jebel Marra volcanic complex relative to the main tectonic elements in region west of Sudan [49].

Figure 25 depicts Darfur doming and thinning of the lithosphere as manifested in a large negative Bouguer gravity anomaly associated with volcanism[49]. Thinning of lithosphere and origin of the uplift or doming refer to the upwelling of hot asthenospheric mantle which is form volcanic activity as a result [51]. Jebel Marra's volcanism age ranges from Miocene to recent times, and it is stratigraphically divided into an old and a new Series separated by an unconformity [50].

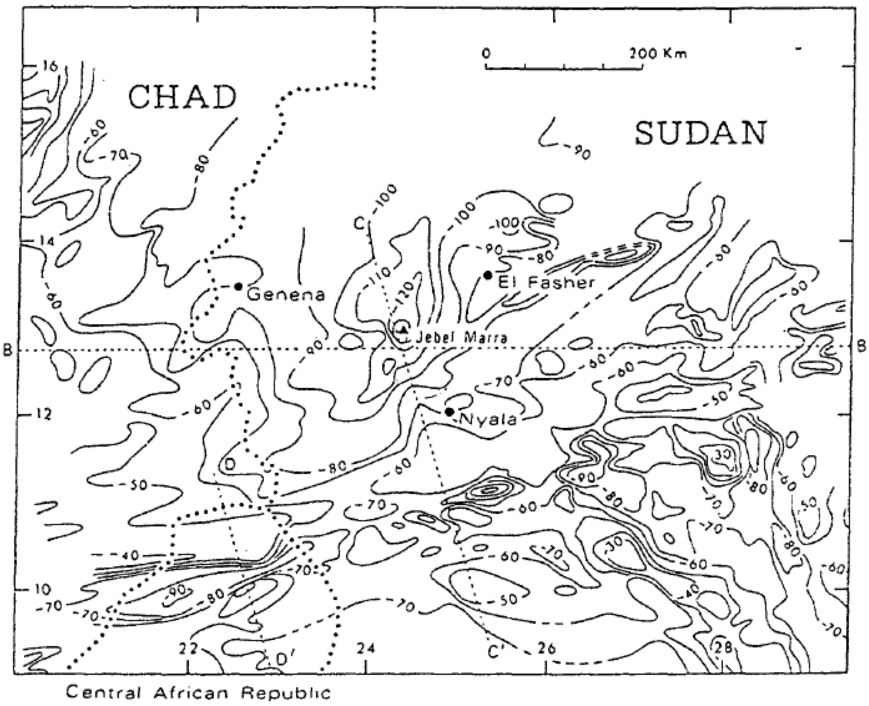


Figure 25 Bouguer gravity anomaly map of the Darfur dome; contour intervals are given in 10 mGal .

Jebel Marra volcano is dormant and consist of well develop caldera in the summit area commonly referred to as a crater, which is about five kilo-meters in diameter at a height of over 2,000 meters and it surrounded by basalt cliffs whose rise from 500-1,000 meters above the floor attaining a maximum height to 3,024 meters in the west [36]. Many reports mentioned that there is a potential of geothermal resource in Jebel Mara [29][30]. Numerous surface thermal manifestations have been reported also such as the presence of hot springs and fumaroles in the Deriba crater [36]. A caldera of Jebel Marra has two crater lakes locally known as the Deriba lakes. A larger lake is shallow and has a maximum depth of 11.6 m and saline (natron), nearly has 2.5 kilometers in length, which occupies part of the eastern floor of the caldera. The second one located in a central cone of the Caldera, compare with the previous one is about 1 km in diameter, deeper with a maximum depth of 108.8 m and brackish. Moreover, it is surrounded by walls of ash and tuff, and sometimes pumice [36]. Volcanic rocks of Jebel Marra overlie the Precambrian basement rocks, and it consist of basalts, trachytes, pyroclastic rocks ,Vents, plugs and scoria cones are ubiquitous across the massif Figure 26 [37]. All available data represent a surface or shallow data so geological factors score: (2).

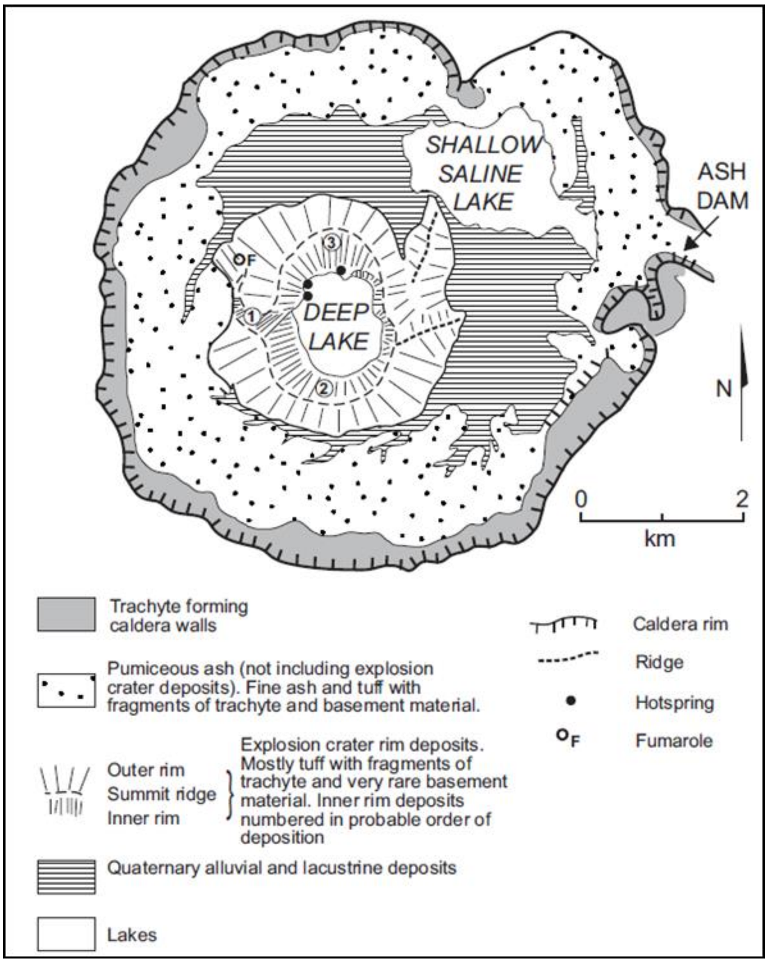


Figure 26 Geological map of the Deriba caldera, Jebel Marra [36].

(2) Geophysical factors

There is no geophysical method applied or design to study geothermal system in the area. Only regional gravity surveys had been implemented and recorded a large negative anomaly in the Jebel Mara area of 50 mGgal in amplitude, which gives idea of the regional geology as shown in Figure 25 [49]. Therefore, geophysical factors scored as (1).

(3) Geochemical factors

Geochemical data of Jebel Marra had been collected from many studies [36][31][43]. First study carried out it was first biological survey of the streams and Deriba lakes in Jebel Marra. Some of the important physical and chemical characteristics of the Deriba lakes are shown in Table 1 below.

Table 1 Physical and chemical characteristics of the Deriba Lake [36].

	Small Dariba Lake (surface sample)	
Date	11/1/66	13/1/66
Temperature in °C	17.9	18.05
pH	9.4	9.8
Alkalinity (HCO_3+CO_3) (meq/L).	47.5	147
Na (mg/L)	1,600	6,200
K mg/L	95	585
NH_3 (as N) mg/L	Nil	Trace
NO_3 (as N) mg/L	Nil	Nil
NO_2 (as N) mg/L	Trace	Trace
SiO_2 mg/L	10	24
P_2O_6 mg/L	0.02	5.2
Cl mg/L	778	2,580
Dissolved O_2 mg/L	6.2	8.2

An UNESCO team reported many hot springs in Jebel Marra and also analyzed some samples as shown in the Table 2.

Table 2 Chemical values in mg/kg; isotope composition in per mille vs. SMOW [31].

Springs	Hami Rotoki	Roj Roja	Nabag FilFil
Location coordinates	12° 18 '195 N 24° 13' 020 E	12° 59' 862 N 24° 13' 573 E	12° 59' 964 N 24° 34' 039 E
T °C (quartz)	128	167	109
Na+	146	1384	1,014
K+	5.6	6.8	59.4
Ca++	6.1	26.7	34.2
Mg	0.1	28.7	23.3
HCO_3^-	195	2,566	2885
Cl-	44	838	43
F-	13.1	<1.0	7.3
SO_4^-	83.0	<1.0	12.6
B	<0.2	4.5	0.3
SiO_2	84	164	59
TDS	577	5,022	4,155
$\delta^{18}O$	-6.58	-1.15	-7.91
$\delta^{2}H$	-46.	-5.6	-53.3

Furthermore, a hydrochemical investigation study for assessing water quality has been conducted to investigate possible sources of dissolved ions in hot spring water in some parts of the Jebel Mara Mountain in the Darfur region of Sudan [43]. Samples collected from hot springs near Koronga village on Jebel Mara were analyzed for significant solutes and trace elements as part of a more extensive study to characterize the geochemical signature of these groundwater [43]. According to the study's findings, hottest spring waters have high levels of hydrogen ion concentration (pH) and electrical conductivity (EC), as well as total hardness (TH), and total dissolved solids (TDS) [6]. Bicarbonate concentration (HCO_3), sodium (Na+), and magnesium (Mg++) concentrations are also higher [6]. The high pH, TDS, TH, Na, and HCO_3 values are all due to ion dissolution from the study area's rock-bearing minerals. Concentrations of iron (Fe), copper (Cu), lead (Pb), iodine (I), and zinc (Zn) are quite normal, but manganese (Mn) concentrations are high. In the previous studies, the hot springs waters were classified as calcium-magnesium-sodium bicarbonate, medium conductivity-salinity, and low sodium content. Furthermore, previous studies reveal that based on the obtained data, the geothermal waters of the Jebel Mara area are of meteoric origin [43]. Therefore, based on the available geochemical data the score is (3).

3.1.3 Reservoir availability factors

(1) Areal extension

Several hot springs and craters where two lakes (Deriba lakes) have been observed and reported, but it is challenging to state the actual number and location of thermal events in Jebel Marra and surrounding areas [36][20][31][43]. The main volcanic feature of Jebel Marra consists of a crater of 5 km in diameter near the south end of the mountain. This crater contains two lakes (Deriba lakes) and is a massive explosion a few thousand years ago. The crater geology and the lake diameter, as shown in figure 4 above, the width of Deriba lakes more than one Kilo. Areal extension of Jebel Marra score (3).

(2) Exit temperatures

Different surface temperature has been measured by UNESCO team in different hot springs located in Jebel Marra (37-57 °C) [31]. Exit temperatures score: (1).

(3) Shallow reservoir temperature

As mentioned above because of the gap in data and missing detailed investigations of Jebel Marra area, shallow reservoir temperature score is (0).

(4) Surface fluid flow factors

Two hot springs were found with flow rates (1-2 L/s each) [31] so the surface fluid flow score is (3).

(5) Structural control

Tertiary basalt is associated with thermal waters, and heat for such thermal waters is collected during deep circulation in fractured basalt, linked to tectonic or volcanic activity [43]. Structural control score (3).

(6) Heat source:

UNESCO mission reported that Gravity anomaly detected in the Jebel Marra area indicates up-dome and crustal thinning and this would mean that the source of magma heat is closer to the surface than usual [31]. Heat source of Jebel Marra score (3).

(7) Drilling depth

There’s no well data reported from wells in Jebel Marra area so drilling depth score: (0).

3.1.4 Marketing availability factors

(1) Distance to higher voltage power lines

Jebel Marra is located in the remote area where is sever lack of infrastructure and also because of security issues in the area. As shown in Figure 27 below the nearest hot spring in Jebel Marra is more than 15 km from power any line. Therefore, distance to higher voltage power lines score: (1).

(2) Terrain of power line

Jebel Marra is a volcanic complex with basalt as the dominant rock type, but trachyte and phonolite are also found locally. The Jebel Mara is described as a massive crater with a diameter of 5 km and has two crater lakes, one saline (natron) and the other relatively fresh, surrounded by ash and tuff walls, pumice occurs locally, and pyroclastic rocks occur near the crater.[43][31][20]. Jebel Marra has a mountainous terrain as shown in Figure 28 and the terrain score: (1).

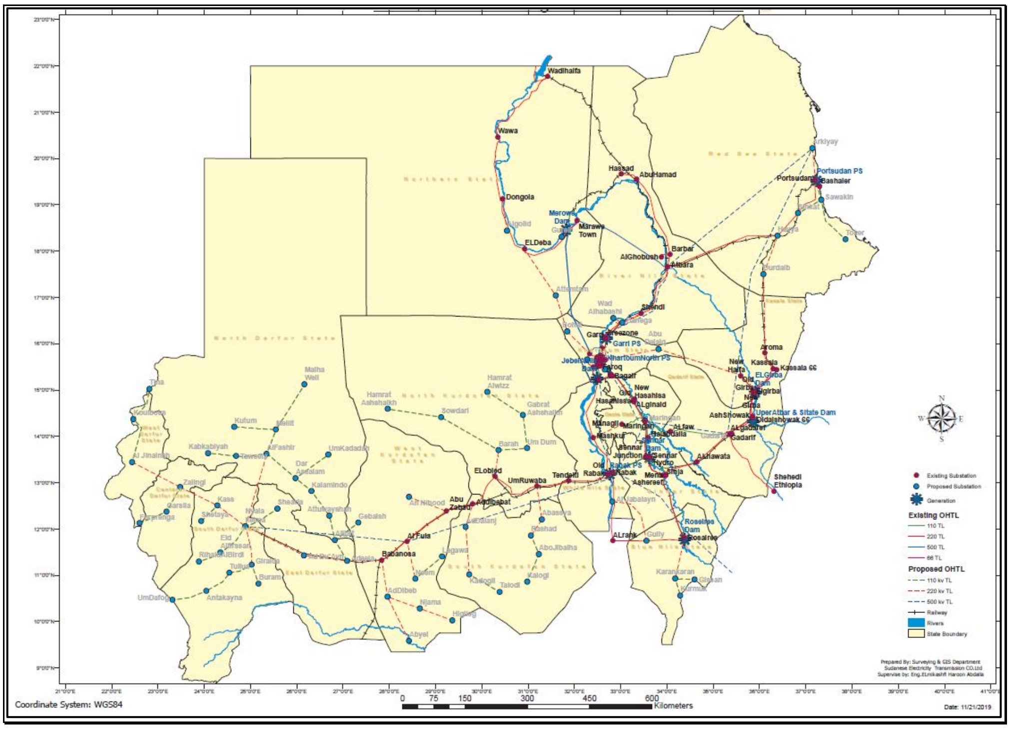


Figure 27 Map of electricity transmission network of Sudan (Source: Sudanese Electricity Transmission Co. Ltd).

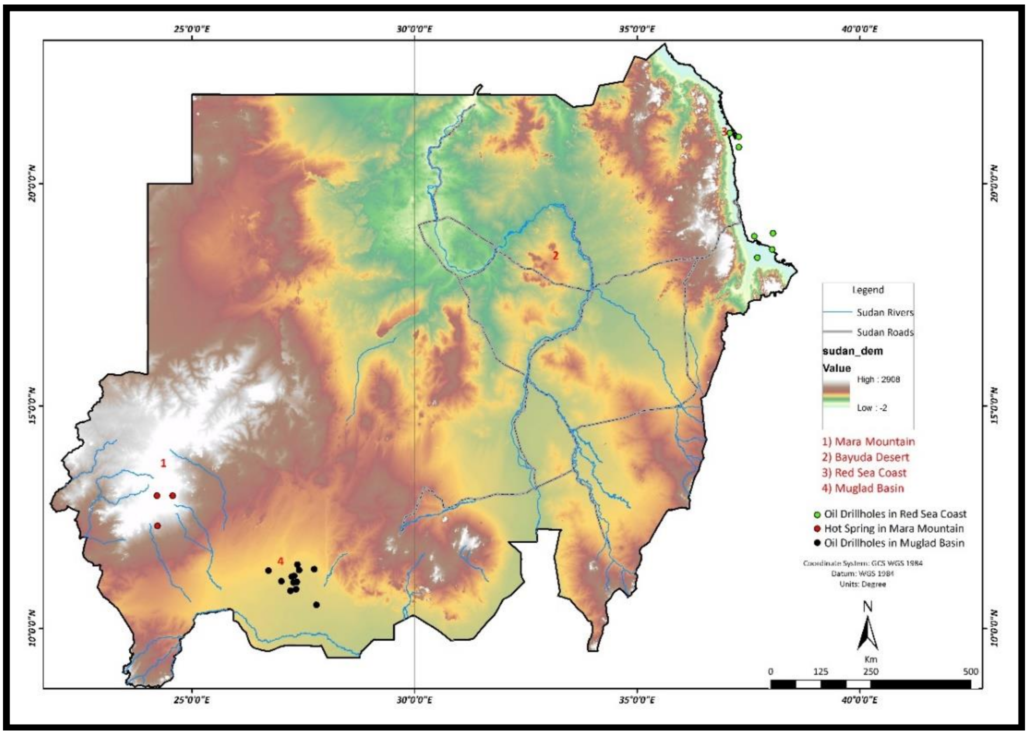


Figure 28 Topographic map of Sudan shows location of geothermal potential areas in Sudan.

(3) Terrain of development site

As mentioned in the above factor Jebel Marra has mountainous terrain so terrain of development site score: (1).

(4) Distance from well to plant site

As a result of information and data gap still the understanding of geothermal system and the prospect area is not mature to figure out a well location. Distance from well to plant site score: (0).

(5) Proximity to market or production areas

Geothermal system of Jebel Marra area so far is not known and understood well to locate the prospect area and measure the distance to the production areas or the market of local people. Therefore, the proximity to market areas score is (0).

3.2. Bayuda Volcanic Fields

3.2.1 Land use availability factors

(1) Accessibility factor

Bayuda volcanic fields (BVFs) are located in the Bayuda Desert, situated inside the Nile River's great Nile River in northern Sudan. It is located approximately 400 km north of Khartoum, south of the Nubian Desert. The wide bend in the Nile River at Abu Hamed, bordering Atbara to the northwest and Merowe to the east defines BVF and is accessible through Marowe-Atbara highway shown in Figure 28. Accessibility among BVF was difficult while implementing a geoscientific survey of Bayuda, which effectively affects the quality of collected samples and the target area coverage. [39]. Accessibility factor score (2).

(2) Terrain factors

As mentioned above Bayuda area is consists of wadis, dunes and small scale farming along the river Nile Figure 29. Terrain factor of Bayuda score (2).

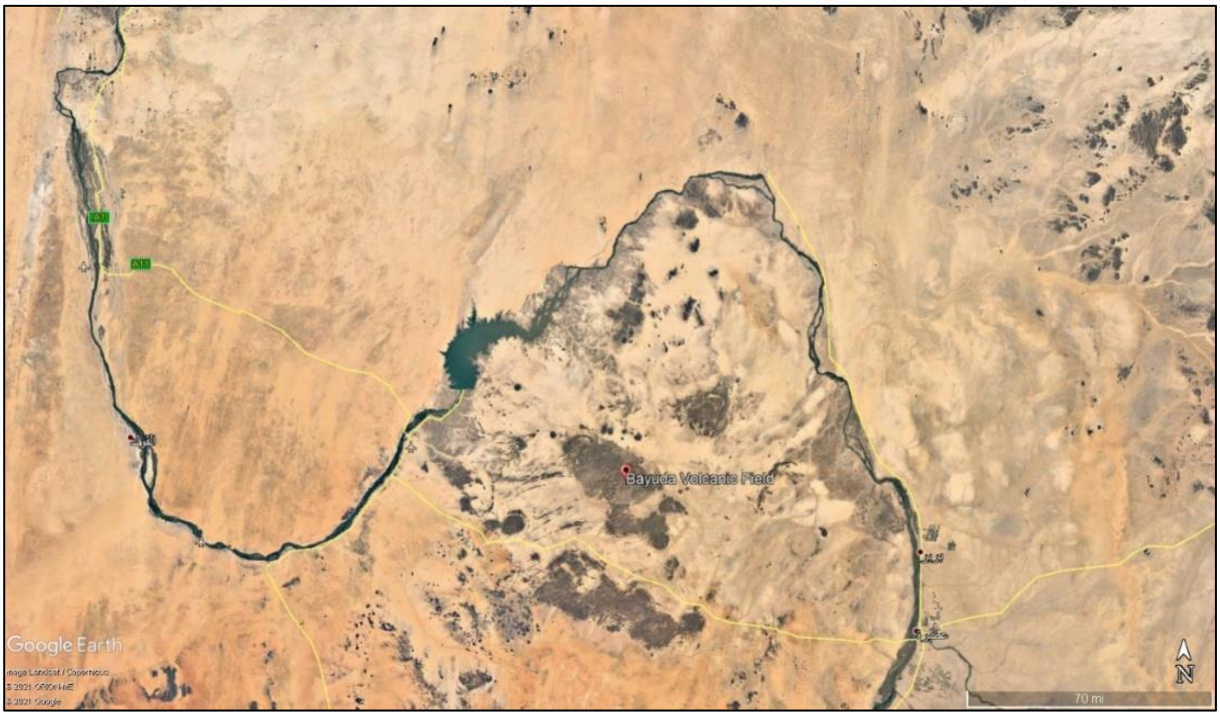


Figure 29 Bayuda volcanic fields image explain the accessibility and terrain. Source: Google Earth. Scale bar 70 miles (112 km).

(3) Risk of natural hazards factors

BVF is located in the south of the Nubian Desert, which is part of the Sahara Desert. The Sahara Desert is without a doubt the most significant source of dust, emitting roughly four times as much as Arabian deserts, as shown in Figure 30 [52]. Depending on the time of year dust storms occur at changing frequencies in the Middle East. The Middle East is a known dust hotspot, particularly during the summer months.

Then the dust storms in the region are frequently associated with Northern winds [53]. Sudan, Iraq, Saudi Arabia, and the Persian Gulf have the most dust storms overall [54]. The risk of natural hazards score is (2).

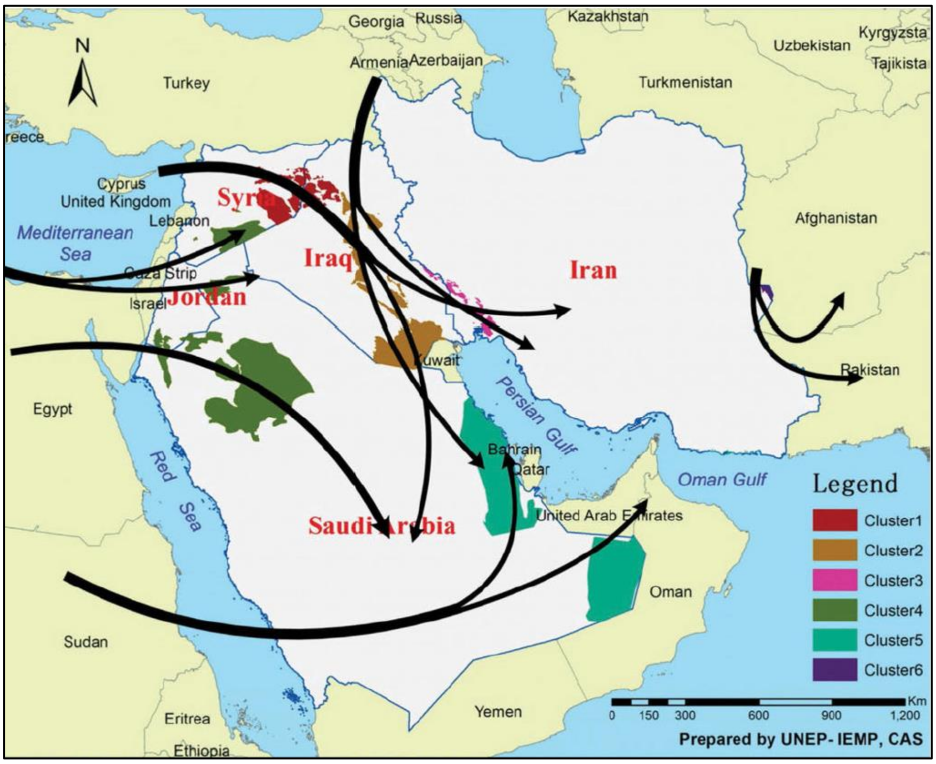


Figure 30 Middle East and North African (MENA) sand and dust storms pathways as well as known source clusters [19].

(4) Security factors

As a result of the Bayuda location in the desert, it is sparsely populated and inhabited by nomads who set up temporary homes. The settlements are mostly clustered around water wells, possibly to reduce the distance traveled while fetching water. Thereby, no security issues have been recorded or mentioned in the available data. Security factor of Bauyda score (3).

(5) Owner attitude

The main activity is livestock farming, with an emphasis on indigenous livestock. Small-scale irrigated agricultural activities are practiced by communities living along the Nile. The residents are incredibly hospitable, as reported by KenGen team while conducting the survey [39]. Owner attitude score (3).

3.2.2 Past exploration availability factors

(1) Geological factors

Basaltic volcanism of Sudan has persisted intermittently since the Cretaceous with the volcanism of the Bayuda volcanic fields (BVFs), which form part of the youngest period of volcanism [55]. Bayuda volcanic fields represent extinct volcanoes as noticed by Gregory and Grabham [56]. BVF occurrences are a result of repetitive vertical motions within a drifting plate and exhibit intense volcanism which present volcanic centers among Bauyda desert such as: Wadi Abu Rugheiwa Volcanic Field (over 500 centers), Shaq Umm Bosh volcanic field (around 300 centers), Wadi Muqaddam volcanic field (40 centers) [55]. The volcanic eruptions erupted materials that are mainly basaltic lava flows and plugs with minor rhyolitic lava flows and pyroclastics [39]. Crustal doming associated with volcanicity in BVF as inferred from geological and topographical evidence [57]. Geological mapping had been carried out in the Bayuda volcanic field and figured out the following features: the rock outcrops, volcanic centers, geothermal surface manifestations such as hydrothermally altered grounds, structural features such as faults, dykes, fractures, joints and folds as shown in Figure 31 [39].

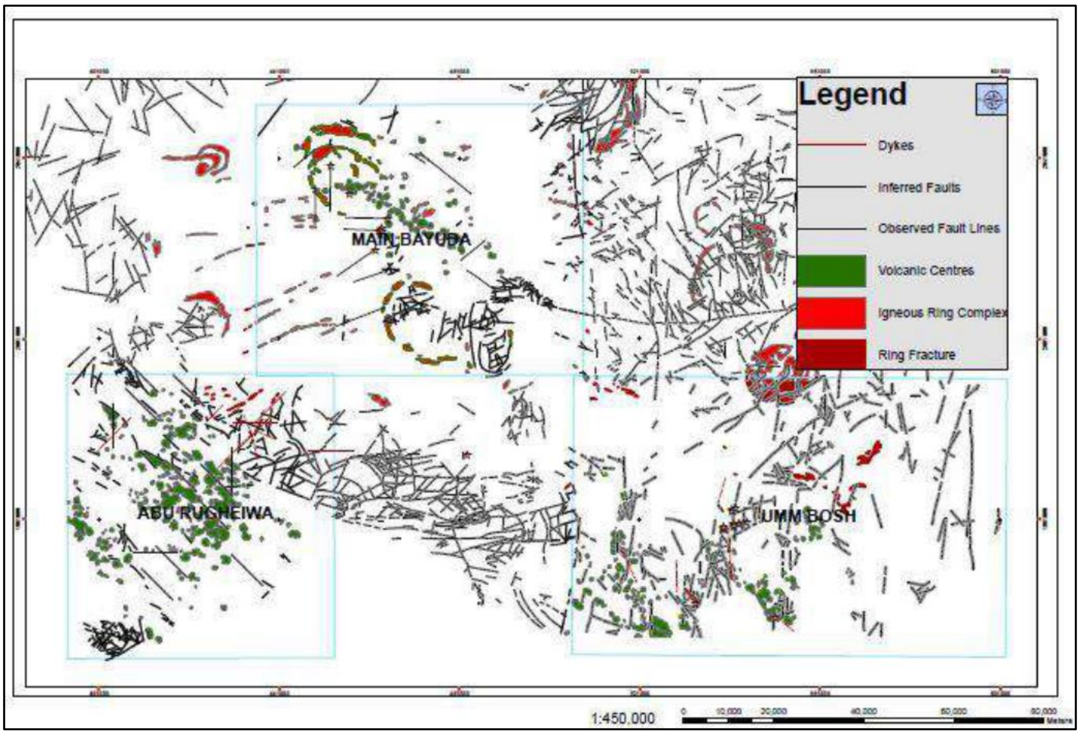


Figure 31 Structural map of Bayuda Volcanic Fields.

The main hydrothermal alteration minerals of BVF are kaolinites and smectites, with minor illites and chlorites. They are found in association with secondary mineral assemblages like quartz, calcites, and gypsum. Kaolinites are formed primarily as a result of hydrothermal changes that result in the decomposition of orthoclase feldspars under acidic conditions. Smectites formed as a result of the weathering of basic rocks with high magnesium potentials, such as basalts and gabbro, whereas chlorites are commonly found as hydrothermal alteration products of ferromagnesian minerals [39]. Referring to the conceptual model, the presence of NW-SW trending volcanic centers, volcanic cone sheets, and plugs in the Main Bayuda area suggests the presence of a structurally controlled magma source beneath. The presence of ring faults and fractures, as well as ring dykes surrounded by granite and granitic gneisses and rhyolitic dykes that appear to converge towards the ring complexes, particularly in the Main Bayuda volcanic field, could be the host of the ring dykes, which are likely heat sources as shown in Figure 32 [39]. Geological factors of Bayuda scored as (3).

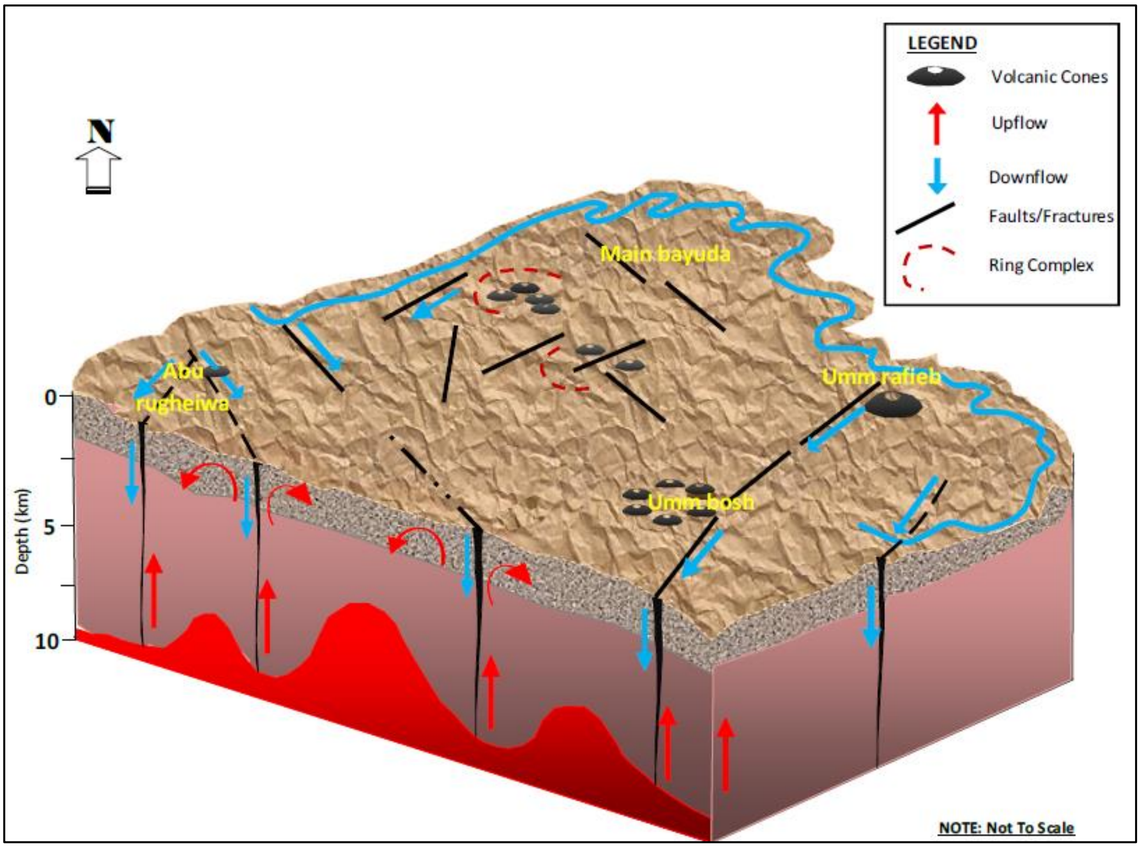


Figure 32 Conceptual model of Bayuda geothermal prospect [18].

(2) Geophysical factors

Transient electromagnetic (TEM) and magnetotelluric (MT) resistivity soundings were performed in BVF. MT is expected to go deeper than TEM, which is mean the shallower and deeper depth were covered as shown in Figure 33 [39]. Geophysical factors score (3).

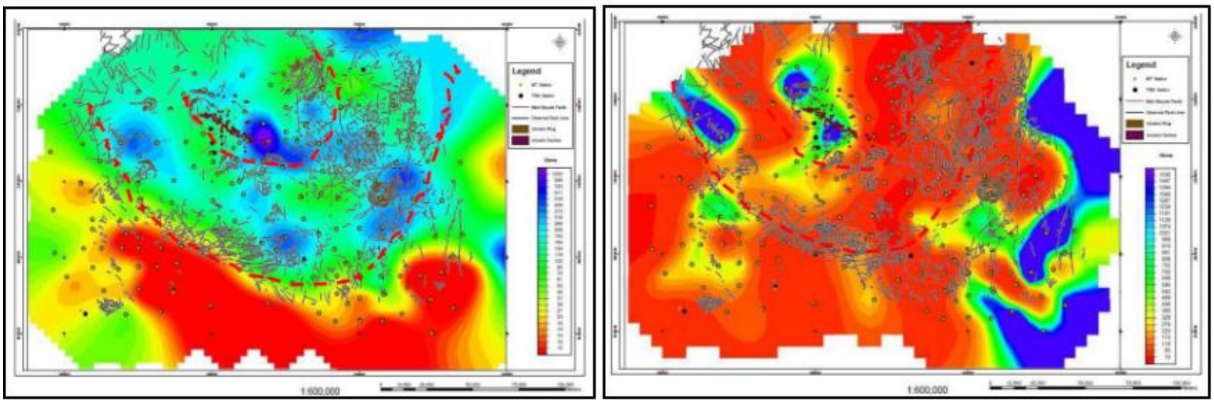


Figure 33 Resistivity iso-map at 300 m asl (above sea level) and 8, 000 m bsl (below sea level) generated from 1D Occam inversion.

(3) Geochemical factors

Water samples were collected from shallow groundwater in BVF that is primarily rain fed. Anion and cation analysis had been done. The analytical results of the anions and cations of the water components were plotted using the Golden Software GRAPHER as shown in Figure 34 to 37 [39]. Geochemical factors score (3).

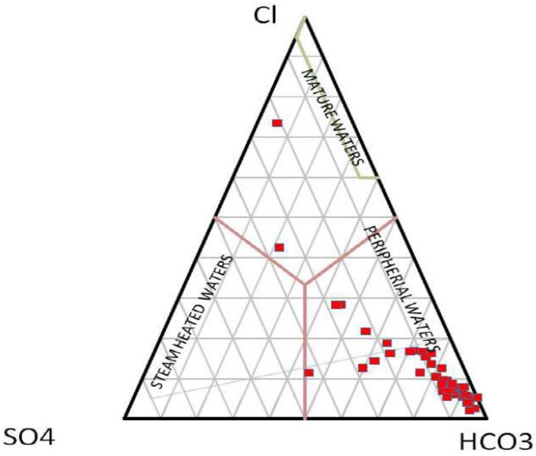


Figure 34 Sulphate-chloride-bicarbonate ternary diagram showing the classification of selected water samples.

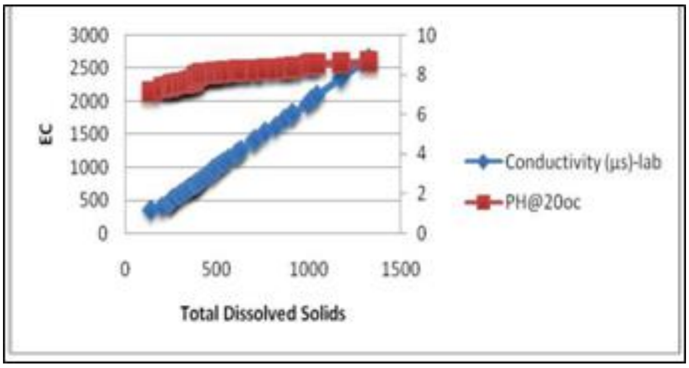


Figure 35 Graph showing the pH and salinity measurement of the water samples.

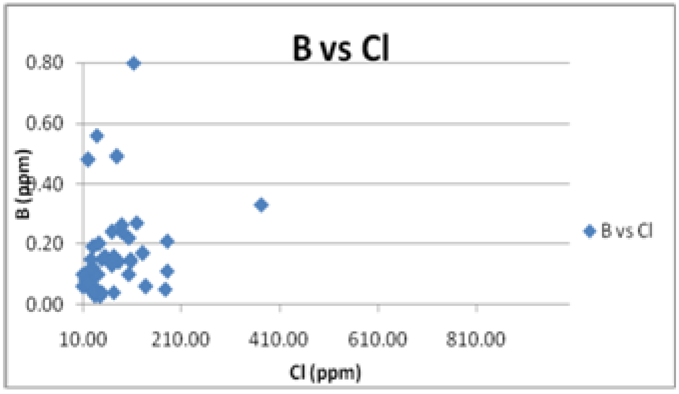


Figure 36 Plots of boron verses chloride concentrations.

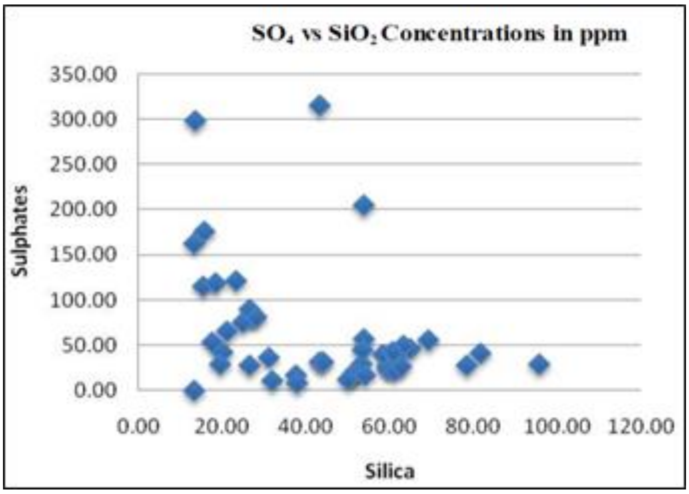


Figure 37 Plot of Sulphates verses silica concentrations in ppm in the water samples.

3.2.3 Reservoir availability factors

(1) Areal extension

The Bayuda volcanic area lacks typical geothermal surface manifestations such as fumaroles, steaming or hot grounds, hot springs, and mud spools that are found in most geothermal fields. However, in a few isolated areas in the Main Bayuda and Umm Bosh, there are scanty altered grounds that indicate the alteration process of hematization, calcitization, and silicification [39]. Areal extension score (0).

(2) Exit temperatures

As mentioned above because of the absence of geothermal manifestations, exit temperatures have not been recorded in BVF region. Exit temperature score (0).

(3) Shallow reservoir temperature

The geology of Bayuda is complex and characterized by lithology of all the three main rock types. Because of their lithology permeability, basalts, sandstones, meta-volcanics, and meta-sediments are the most likely reservoir rocks. The reservoir temperature is thought to be higher than 200 °C based on the geophysical interpretation and the clay minerals observed [39]. Shallow reservoir temperature score (3).

(4) Surface fluid flow factors

Due to the absence of any geothermal manifestations no surface fluid flow has been reported for Bayuda volcanic field. Surface fluid flow factor score (0).

(5) Structural control

The drainage system in Bayuda is structurally controlled, as evidenced by the Wadis drainage patterns, which correspond to the dominant NW-SE structural trends. On a local scale, these erosional features (wadis) contribute to the recharge of the Bayuda geothermal prospect. It is assumed that the River Nile plays a significant role in recharge via deep-seated faults [39]. Structure control score (3).

(6) Heat source

There is a preferential magma up rise in areas where volcanic activity is currently concentrated, such as the Bayuda volcanic system, which gives rise to hot magmatic bodies close to the surface. Magma chambers at shallow depths are thus likely to exist beneath the volcanic centers in the Bayuda prospect [39]. Heat source of Bayuda score (3).

(7) Drilling depth drilling depth

KenGen's study reported that few boreholes in BVF drilled deep and diesel-run electric pumps drive them [18]. Drilling depth score (3).

3.2.4 Marketing availability factors

(1) Distance to higher voltage power lines

BVF a crossed by high voltage power line (500 kV) and located near Merowe dam as shown in Figure 6. Distance to higher voltage power lines score (3).

(2) Terrain of power line

Bayuda area is a desert with flat terrain and volcanic hills and more than 90 eruptive centers, including cinder cones, craters, and plugs, as shown in Figure 38 [39] score (2).

Figure 38 Photos showing a part of Bayuda Desert and sand dunes.

(3) Terrain of development site

As mentioned above, the terrain Bayuda volcanic fields are generally low lying, rising to an average elevation, and are made up of shrubs, wadis, and dunes. The terrain of power line score (2).

(4) Distance from well to plant site

KenGen's study identified two prospect areas for further exploration activity to prove the potentiality of geothermal energy in Bayuda volcanic field [18]. So far, no wells have been drilled yet to determine the distance from the well to the plant site. Distance from well to plant site score is given (0).

(5) Proximity to market or production areas

In terms of agriculture, livestock farming is the primary activity, with an emphasis on indigenous livestock. The communities that live along the Nile River engage in small-scale irrigated agricultural activities [39]. Bayuda volcanic field is located beside the Nile River, so proximity score (3).

3.3 Red Sea area

3.3.1 Land use availability factors

(1) Accessibility factor

Geothermal potential sites of the Red Sea located both offshore and onshore along the coastal plain, as shown in Figure 18 [38]. Temperatures in drill holes near the central Red Sea trough are generally the highest while near the shore is vary, and high-temperature gradients have been observed in some locations. The temperature gradients in the wells drilled on the mainland coastal plain are relatively low. On the other hand, the significant potential was reported for the Suakin area (offshore) (Figure 37), located approximately 100-170 km south of Port Sudan [20]. Accessible factor score (1) because the onshore area (Dungnab Island) is the highest potential area in the Red Sea area.

(2) Terrain factors

The Durwara-2 well is the most potential well located near the mainland on the edge of Durwara Island, while the other wells (Bashayer-1A and Suakin-1) are offshore or in the sea, as shown in Figure 39 [38]. Terrain factors score (2) for the island and offshore locations.

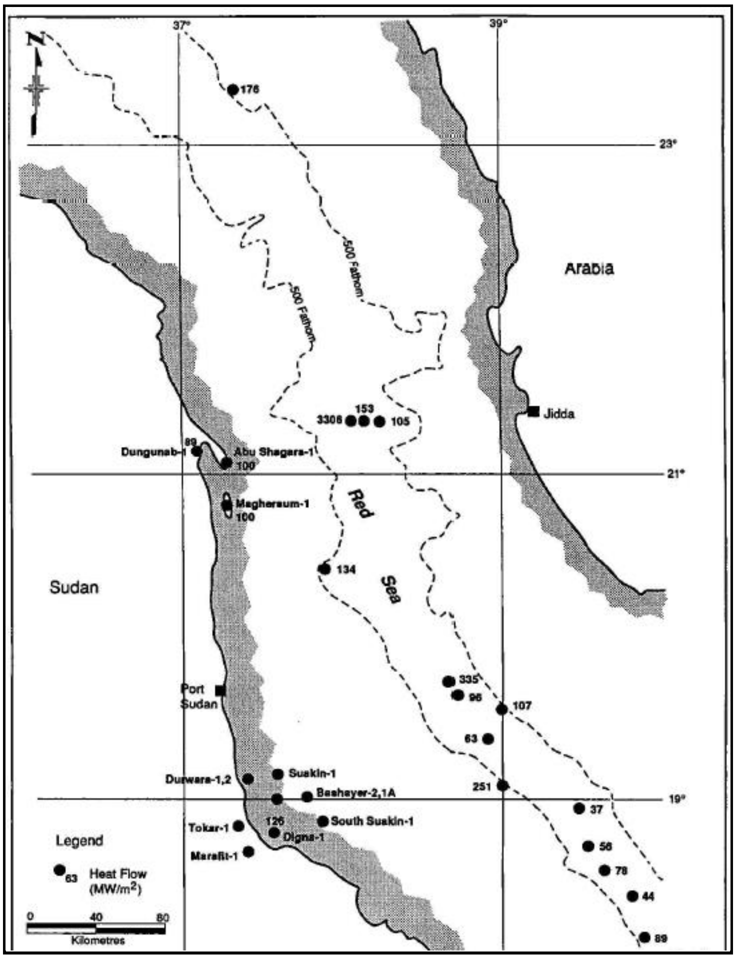


Figure 39 Heat flow data and drilled well in the central Red Sea region.

(3) Risk of natural hazards factors

Red Sea potential area is consisting of onshore and offshore areas, as shown in the previous Figure 39. The Red Sea is vulnerable to the hazards that accompany the coastal and sea. Heavy rains and floods were reported in Red Sea state in 2018, particularly in its capital Port Sudan, causing infrastructure damage, casualties, and disruptions [58]. The Sahara Desert and the Arabian Peninsula, both on either side of the Red Sea, are among the world's most dust-producing regions [52]. NASA's Aqua satellite is equipped with a moderate resolution imaging spectroradiometer (MODIS), which captured the natural-color image of a dust plume blowing over the Red Sea in 2012. Unfortunately, the dust merged with the land surface below Sudan, leaving only a shadowy outline Figure 40 (upper left corner).[59]. Dust was thick along the Sudanese coast, but it thinned slightly to the southeast as visible in the high-resolution image. Risk of natural hazards factors score (2).

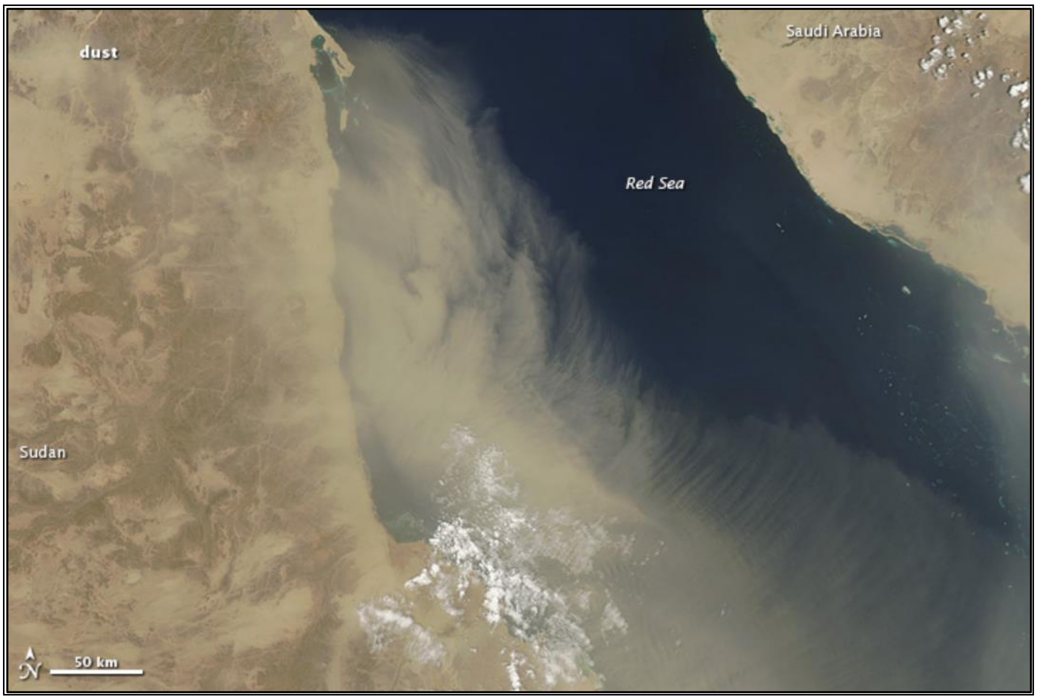


Figure 40 Dust plume blowing over the Red Sea (MODIS) on NASA's Aqua satellite.

(4) Security factors

The Red Sea and its surroundings, including many countries in the Horn of Africa, have recently received increased global attention. There are concerns that the shared space is not being managed effectively, and new approaches are needed to address them. Current threats in the maritime space are primarily driven by non-secure environments and the rise of non-state and non-governmental actors. However, no significant disruptions to maritime traffic have occurred to date [60]. Security factor score (3).

(5) Owner attitude

As mentioned before, the operations of oil exploration along the Red Sea were carried out smoothly. Potential areas of geothermal located along the Red Sea coast and offshore on the edge of the island, as shown in Figure (16), where there are no people in those areas. Owner attitude score (3).

3.3.2 Past Exploration Availability factors

(1) Geological factors

The Red Sea area has not geothermal studies oriented. However, Robertson's research reported that Rift faulting in coastal areas is accompanied by high heat flow anomalies in onshore and offshore oil exploration wells [17]. There is also significant rifting in the Southern Red Sea Hills, where Quaternary basaltic and acidic lavas have been mapped [17]. Exploration of hydrocarbons along to the Red Sea launched in the late 1950s when AGIP Mineraria purchased three offshore oil concession blocks totaling approximately 8,500 km^2 and figured out the profile in Figure 41 [61] . Durwara-1, the first well drilled, encountered minor oil and gas shows in 1961. Drilling operations were halted until 1975 when Chevron discovered gas in the Bashayer-1A well. Up to 1998, a total of 13 wells (10 wildcats and three appraisals) were drilled, with two discoveries in Bashayer-1A and Suakin-1 Table 3. The Red Sea Petroleum Operating Company (RSPOC) has resumed exploration in 2010 and drilled two wells, Talla-1 and Tokar, who both were dry. Table 3 shows the activities of petroleum oil companies along to the Red Sea area. Geological factors score is (3).

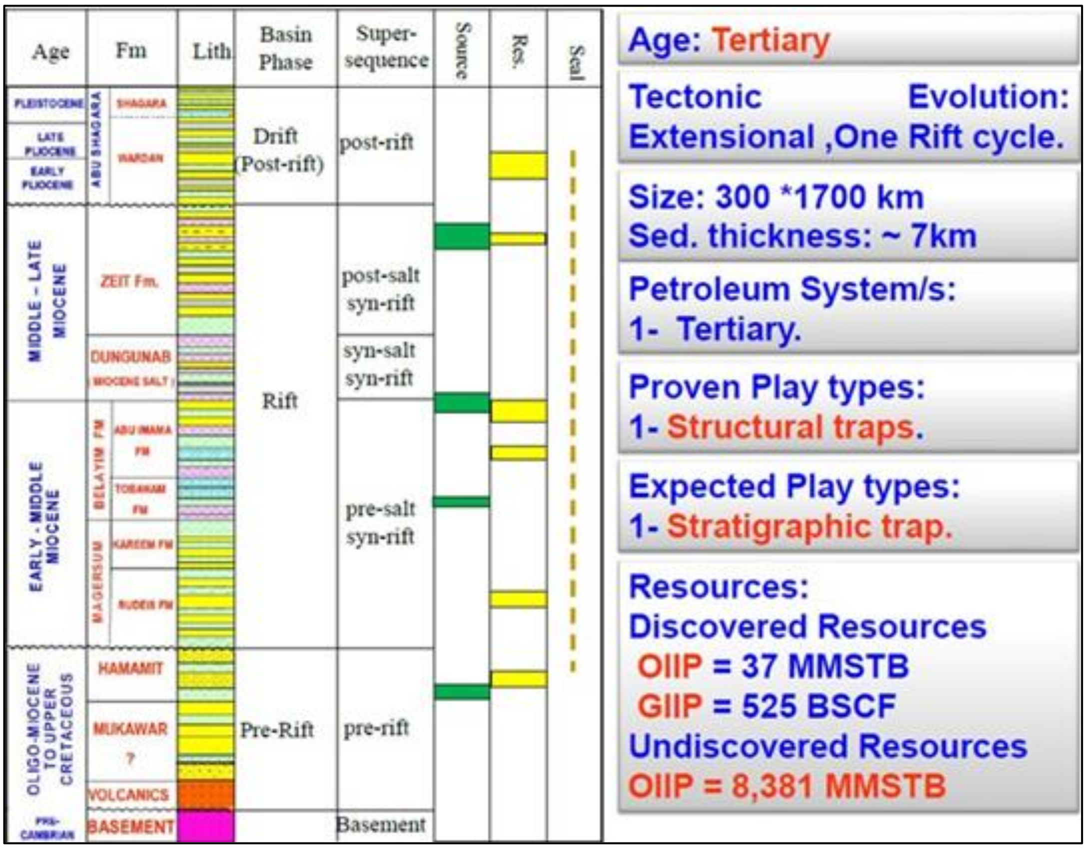
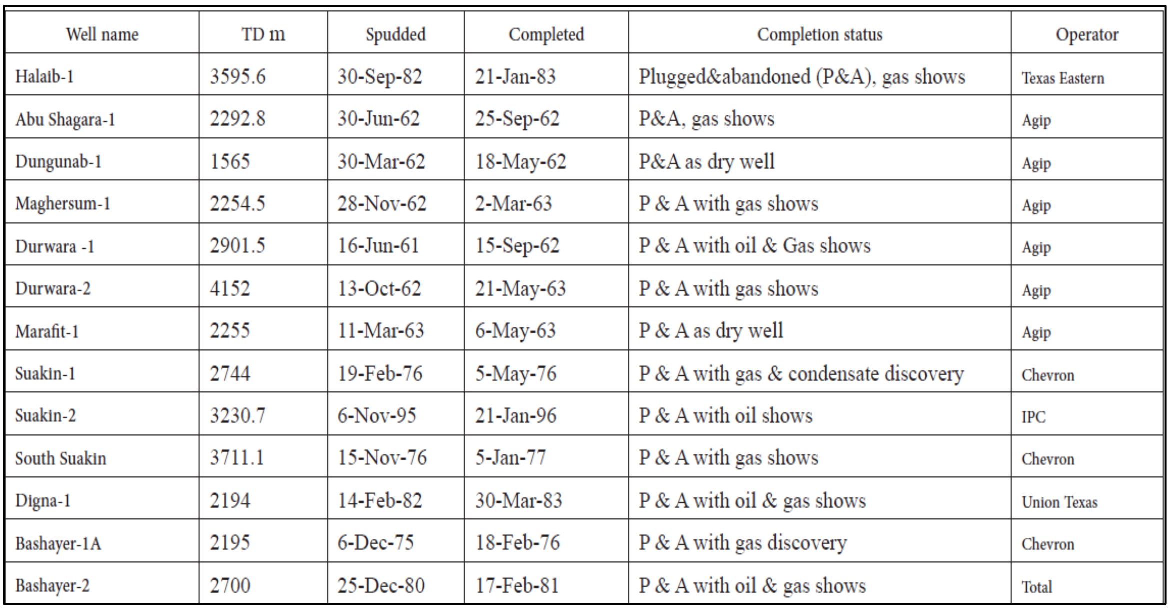


Figure 41 Red Sea profile basin with proven petroleum systems and discoveries.

Table 3 Summary of the drilled wells in the Sudanese Red Sea rift (after EREX, 2008) [62].



Well name	TD m	Spudded	Completed	Completion status	Operator
Halaib-1	3595.6	30-Sep-82	21-Jan-83	Plugged&abandoned (P&A), gas shows	Texas Eastern
Abu Shagara-1	2292.8	30-Jun-62	25-Sep-62	P&A, gas shows	Agip
Dungunab-1	1565	30-Mar-62	18-May-62	P&A as dry well	Agip
Maghersum-1	2254.5	28-Nov-62	2-Mar-63	P & A with gas shows	Agip
Durwara -1	2901.5	16-Jun-61	15-Sep-62	P & A with oil & Gas shows	Agip
Durwara-2	4152	13-Oct-62	21-May-63	P & A with gas shows	Agip
Marafit-1	2255	11-Mar-63	6-May-63	P & A as dry well	Agip
Suakin-1	2744	19-Feb-76	5-May-76	P & A with gas & condensate discovery	Chevron
Suakin-2	3230.7	6-Nov-95	21-Jan-96	P & A with oil shows	IPC
South Suakin	3711.1	15-Nov-76	5-Jan-77	P & A with gas shows	Chevron
Digna-1	2194	14-Feb-82	30-Mar-83	P & A with oil & gas shows	Union Texas
Bashayer-1A	2195	6-Dec-75	18-Feb-76	P & A with gas discovery	Chevron
Bashayer-2	2700	25-Dec-80	17-Feb-81	P & A with oil & gas shows	Total

(2) Geophysical factors

According to EREX [62], several surveys were conducted to collect gravity, magnetic, and seismic data, as follows: In 1960, AGIP acquired ground magnetic and gravity surveys over the Abu Shagara Peninsula near Abu Shagara-1, Dungunab-1, and Magersum-1. Another survey was conducted south of Port Sudan, over the Tokar Delta region. In 1968, Conoco acquired an airborne survey over the Tokar Delta's offshore portion. The Woods Hole Oceanographic Institution collected very deep water data in the Red Sea's axial trough in 1971. In 1975, Oceanic acquired a marine magnetic survey in water deeper than 1200 feet near the Egyptian-Sudan border and south of Abu Shagara Peninsula. Chevron conducted an airborne magnetic and gravity survey over the Tokar Delta in 1975, concurrent with their offshore seismic program. The Russian Group Technoexport purchased onshore gravity in the Red Sea Hills in 1977, primarily for mineral purposes. Texas Eastern acquired gravity in the onshore area in 1980, concurrent with their Halaib-1 well. Since 1974, approximately 11,400 km of modern digitally recorded seismic data have been acquired, with 4,817 km beyond the shelf break and 6,549 km in shallower coastal water. Based on the information that mentioned above geophysical factors score (3).

(3) Geochemical factors

EREX geochemically analyzed ditch cutting samples (82) from the four wells Suakin-1, -2, South Suakin-1, and Digna-1. The primary goal was to assess the maturity and potential of the source rock in terms of oil. No geochemical data have been obtained from a geothermal perspective. Geochemical factors score (0).

3.3.3 Reservoir Availability factors

(1) Areal extension

Geothermal studies had not been done to figure out the geothermal system elements in the Red Sea area. Areal extension score (0).

(2) Exit temperatures

The Red Sea has no surface manifestation, such as hot springs, so no exit temperature is reported in the area. Exit temperature score (0).

(3) Shallow reservoir temperature

As mentioned before, geothermal elements have not been identifying in the Red Sea area. Shallow reservoir temperature score (0).

(4) Surface fluid flow factors

Surface fluid factors score (0) because of surface geothermal manifestation absence which has not been reported to measure the fluid flow.

(5) Structural control

Structural control of the geothermal system in the Red Sea area is unknown due to the lack of knowledge of the elements. Structural control score (0).

(6) Heat source

Oil wells were drilled in the seabed and along the Sudan coastal plain and have shown that heat-flow values are generally higher in the center of the Red Sea's trough and decrease towards the flanks. Heat production measurements of Sudanese basement granites show a significant depletion of radiogenic heat-producing elements [38]. Heat source score (3).

(7) Drilling depth

As shown in Table 3, the wells in the Red Sea are exceeding 2,000 m, and they are located onshore or offshore. Drilling depth score (3).

3.3.4 Marketing Availability factors

(1) Distance to higher voltage power lines

Port Sudan city is the capital of Red Sea state which is linked by higher voltage lines, as shown in Figure 6. According to the UNESCO report, the Suakin area, located approximately 100-170 km south of Port Sudan, has significant potential. Distance to higher voltage power lines score (1).

(2) Terrain of power line

The physiographic features that characterize the Red Sea region can be divided into three major zones, which are as follows [63]:

a) The Red Sea Hills are a major physiographic feature in the region; they are steeply rising north-south trending mountains from the coastal plain. They stretch more than 200 km from north to south, from the Egyptian to the Eritrean border, with a width of more than 200 km and an elevation of about 2000 m above sea level.

b) The Sudanese coastal plain is 740 km long and 20 km wide, increasing to 40 km on the northern edge at Halaib and 50 km on the southern edge at Tokar Delta. The topography of the coastal plain is generally gentle. It is located between the Red Sea and the eroding scarp that forms the eastern boundary of the Red Sea Hills.

c) The Red Sea area represents a tight marine basin in Sudan that stretches for about 740 km. It across the Eritrean border in the south to the Egyptian border in the north. It has a maximum width of 306 km.

Exploration activities for oil and gas had been carried out along the coastal plain were suspected to be a potential geothermal area. The terrain of power line score (2).

(3) Terrain of development site

The Durwara-2 well is located on the edge of Durwara Island, a few kilometers offshore and 170 km south southeast of Port Sudan, the Red Sea state's capital. This well has the potential to produce geothermal energy [20]. Terrain development site score (1).

(4) Distance from well to plant site

The exact prospect area is unknown and required more exploration work. Therefore, the score of distance from well to plant site is (0).

(5) Proximity to market or production areas

As mentioned in the above section, the most potential area is 170 km from Port Sudan. Proximity to market or production areas score (1).

3.4 Muglad Rift Basin area

3.4.1 Land use availability factors

(1) Accessibility factor

The Muglad Basin is located in southern Sudan and extends among two countries, covering an area of approximately 120,000 km^2 Figure 41 [64]. Muglad basin area, as you can see in Figure 42, is linked by different types of roads paved and unpaved roads. Accessibility factor score (3).

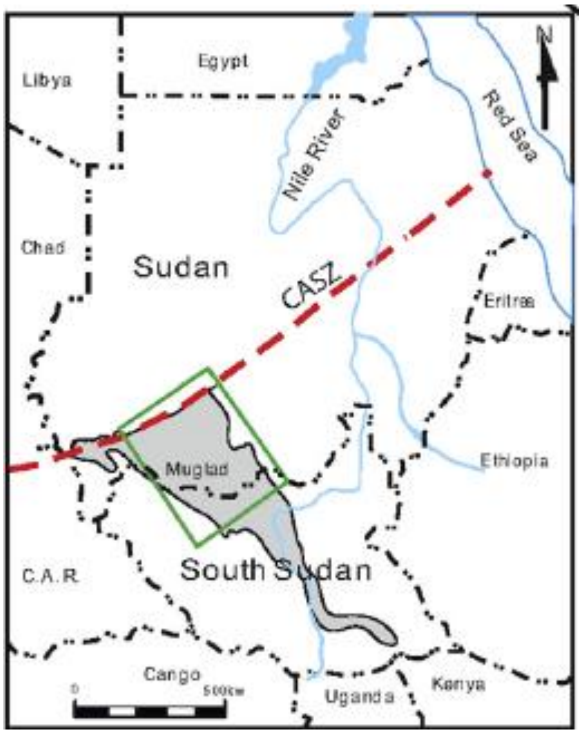


Figure 42 Map of the area of the Muglad Rift Basin [62].

(2) Terrain factors

The terrain is generally flat and covered in most places with loose sands of Tertiary to recent age from the Umm Ruwaba formation [65]. Terrain factor score (3).

(3) Risk of natural hazards factors

In 2018 fracture phenomena were reported in the Fula capital city of the Western Kordufan province, representing one of the provinces located along the Muglad rift basin. GD of geological research authority Dr. Abo-Fatma refers these phenomena to preexisting fractures that were filled by sediments and occurred as a result of flooding and gravity subsidence (Kushnews.net, 29.06.2018). Risk of natural hazards score (2).

(4) Security factors

At all levels of governance, from international, over regional, national, state, to community levels, it is possible to trace how oil operations and utilization have contributed to instability or insecurity, both indirectly and directly. Fighting causes shutdowns or, more subtly, discourages future investment, so security levels impact oil production. The oil–conflict link is widely acknowledged as a worldwide issue. However, it has been exacerbated in Sudan and South Sudan by a geographical and historical accident: the majority of the oilfields are located along the instable former colonial times border between the two countries. The Sudanese and South Sudanese governments employed the oil industry to encourage security situation between the two countries, based on the expected benefit established by Sudan as control of the export infrastructure and South Sudan's possession of most of the oil. There are ongoing dissatisfaction and rumblings of social discontent in Sudan, especially among the Missiriya societies, responsible for widespread low-level insecurity that has hampered oil activities. The kidnapping of Chinese oil operators by Missiriya in 2008 resulted in four fatalities. The government initiated some efforts to address this, and while they have been successful in curbing the unrest, they have not been successful in reducing the underlying reasons. Sudan-South Sudan relations have been unusually cooperative since late 2013, owing to a shared interest in keeping the oil flowing [66]. Security factor score (2).

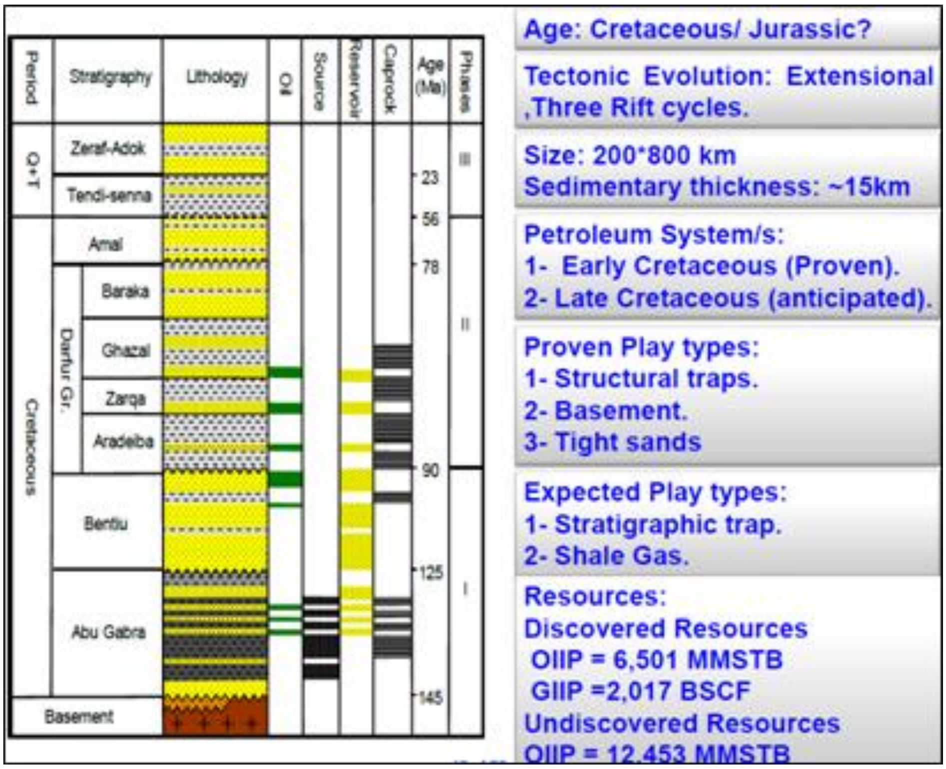
(5) Owner attitude

Although the government may control all of Sudan's oilfields, rebel groups and local societies pose notable threats in some fields. Since southern secession, many of Sudan's remaining oil fields have been located in areas where the increasingly disgruntled Missiriya tribe claims historical rights. Misseriyya tribes are dissatisfied regarding the impact of the oil industry on socio-economic life and development.[66]. Protests erupted in March 2014 at the Baleela oilfield in West Kordofan, fueled by local complaints about a lack of job opportunities, killing four people; during later months, oil workers were kidnapped in South Kordofan at the Kanar field. The government has initiated and trained additional oil police to protect petroleum installations across the country to address these issues [32]. Owner attitude score (1).

3.4.2 Past Exploration Availability factors

(1) Geological factors

The Muglad Rift Basin is one of several large rift basins in the region. The basin is located along southern Sudan and South Sudan, as shown in Figure 12. Numerous studies on the potential and thermal maturity of the source rocks in the basin have been conducted [64]. As mentioned before many studies have been implemented in order to explore and develop the hydrocarbon reserve. Figure 43 shows a generalized stratigraphic column of the Muglad basin. Geological factor score (3).



Age: Cretaceous/ Jurassic?

Tectonic Evolution: Extensional ,Three Rift cycles.

Size: 200*800 km
Sedimentary thickness: ~15km

Petroleum System/s:
1- Early Cretaceous (Proven).
2- Late Cretaceous (anticipated).

Proven Play types:
1- Structural traps.
2- Basement.
3- Tight sands

Expected Play types:
1- Stratigraphic trap.
2- Shale Gas.

Resources:
Discovered Resources
OIIP = 6,501 MMSTB
GIIP =2,017 BSCF
Undiscovered Resources
OIIP = 12,453 MMSTB

Figure 43 Section of Muglad Rift Basin (producing basin) [61].

(2) Geophysical factors

Muglad Rift Basin is the only Oil-producing basin in Sudan, so many operations and geophysical surveys had been carried out along the basin. Chevron began exploration activities in 1975 by conducting Aero-magnetics followed by a helicopter-supported large-area gravity survey [67]. The seismic acquisition began in 1976, and the initial seismic program was steered by gravity and aeromagnetic survey interpretations. Seismic acquired by different companies from 1976 to 1986, 1997, and 2004. The total area covered by 2D and 3D seismic data is approximately 3,718 km^2 and 698 km^2, respectively [68]. Geophysical factors score (3).

(3) Geochemical factors

Muglad Rift basin was exposed to geochemical analysis as targeting for oil exploration. Thousands of rock samples have been analyzed for conventional geochemical analyses, such as whole-rock pyrolysis and organic carbon content, to investigate source rock characteristics, biodegraded oils in the reservoir, and correlate oil between wells. Geochemical analysis of geothermal elements along the Muglad basin is absent. Geochemical factors score (1).

3.4.3 Reservoir Availability factors

No detailed geothermal studies had been carried out in the Muglad rift basin to figured out the geothermal elements and identify the characterization of each one. Therefore, reservoir availability factors such as *(1) areal extension*, *(2) exit temperatures*, (*3) shallow reservoir temperature*, and *(4) surface fluid flow* factors. All these factors are scored (0).

(5) Structural control

According to Robertson Research International company, fault structures that control oil exploration in the rift basin of Sudan have a high potential for deep circulating, hot geothermal fluids [30]. Structural control score (3).

(6) Heat Source

The ACRES study found that the higher gradients are caused by heat from deep within the basin being redistributed by hot connate waters passing up deep-seated faults. Local gradient increases are observed in a few areas, which are thought to be related to igneous rocks encountered by the wells [20]. Heat source score (2).

(7) Drilling depth

Many wells had been drilled along to the Muglad rift Basin by Oil operating companies. The good depths generally are deep and sometimes exceed 4,000 m, as shown in Table 4 [20]. Drilling depth score (3).

Table 4 Bottom hole temperatures of oil wells along Muglad Rift Basin [19].

No	Maximal Depth (m)	Temperature (C°) at maximal depth
1	4,167	119
2	2,896	99
3	2,743	99
4	3,506	110
5	3,738	93
6	2,446	78
7	3,865	136
8	1,640	60
9	4,257	129
10	3,048	99

3.4.4 Marketing Availability factors

(1) Distance to higher voltage power lines

Muglad rift basin is the only producing basin in Sudan and a crossed by a higher voltage power line, as shown in Figure (4). So far, the exact geothermal production area is not known to measure the distance from the higher voltage power lines. Therefore, the score of this factor (0).

(2) Terrain of power line

As mentioned before, terrain is generally flat and covered in most places with loose sands of Tertiary to recent age from the Umm Ruwaba formation [65]. Terrain of power line score (3).

(3) Terrain of development site

Muglad rift basin is a flat area, therefore the terrain of the development site in the future scored (3).

(4) Distance from well to plant site

A detailed study had not been done to identify the exact location of the geothermal prospect and the Mugalad rift basin. Distance from well to plant is unknown and score (0).

(5) Proximity to market or production areas

The oil fields located along the Muglad basin represent production areas. Oils in the Muglad Basin have a wide range of physical properties, including light, normal, and heavy oils, as well as oils with high acidity [69]. Generally, geothermal energy could apply as a tool for enhancing oil recovery (EOR) in the existing fields where the pressure is depleted or in the fields where produce heavy oil [70]. Proximity to production areas score (3).

CHAPTER 4
DISCUSSION AND CONCLUSIONS

4.1 Discussion

4.1.1 Numerical Scoring Assessment

In the Republic of Sudan, geothermal resources have been discussed since the 1960s. However, the geothermal resource has not been developed yet. This study aimed to assess and evaluate Sudan's geothermal resources in preparation for future detailed exploration reconnaissance, such as geophysical, geochemical, and test drilling. The occurrence of hot springs and fumaroles on volcanic areas such as Jebel Marra and Bayuda and the presence of high temperature or high geothermal gradient on the Muglad and the Red Sea coast suggests the possibility of the existence of geothermal resources in Sudan. Assessment has been done to the geothermal resource fields in Sudan based on the available data to mitigate the exploration risk that represents the main challenge of development.

Every factor has a dependent variable, providing a relative score for each potential geothermal area to be calculated. The cumulative factors score for the most potential geothermal resource areas of Sudan (PGRS) assigned and calculated in Table 5 and Figure 43 based on the available data described above; the positive attitude factors design method assessed the potential geothermal sites in Sudan as following:

1. *Land use:* Higher scores for Bayuda, but not maximal scores, and medium values for the Red Sea, Muglad Basin, and the lowest score for Jebel Mara because of the security situation resulting from conflicts between governments and armed groups.
2. *Past Exploration:* Maximal score for Bayuda as studied by KenGen and a lower score for Muglad Basin and the Red Sea although massive exploration activities have been carried on to produce the oil; but no geochemical analysis from a geothermal perspective has been done. Jebel Mara also has a low score as no detailed geophysical surveys have been implemented.
3. *Reservoir:* Highest score for Jebel Mara, but not maximal as it received many missions to study the hot spring phenomena in the area, and higher score for Bayuda area as investigated by KenGen. A lower score for the Muglad Rift Basin although quite many data but it has not been studied in terms of geothermal reservoir characteristics. The lowest score for the Red Sea is given for the same reason as for the Muglad Basin.

4. *Marketing*: Highest score for Bayuda, but not maximal score, and higher score for Muglad Basin. A lower score for the Red Sea and the lowest score for the Jebel Mara area.

Table 5 Positive attitude factors scores of potential geothermal areas in Sudan.

Prospect Areas	**Jebel Mara**	**Bayuda**	**Red Sea**	**Muglad Rift Basin**
1 Land Use Availability				
(1) Accessibility factors	1	2	1	3
(2) Terrain factors	1	2	2	3
(3) Risk of natural hazards	2	2	2	2
(4) Security factors	1	3	3	2
(5) Owner attitude	3	3	3	1
Fractional Score: 15 points	**8**	**12**	**11**	**11**
%	53.33%	80%	73.33%	73.33%
2 Past Exploration Availability				
(1) Geological factors	2	3	3	3
(2) Geophysical factors	1	3	3	3
(3) Geochemical factors	3	3	0	0
Fractional Score: 9 points	**6**	**9**	**6**	**6**
%	66.67%	100%	66.67%	66.67%
3 Reservoir Availability				
(1) Areal extension	3	0	0	0
(2) Exit temperatures	1	0	0	0
(3) Shallow reservoir temperature	0	3	0	0
(4) Surface fluid flow	3	0	0	0
(5) Structural control	3	3	0	3
(6) Heat source	3	3	3	2
(7) Drilling depth	0	3	3	3
Fractional Score: 21 points	**13**	**12**	**6**	**8**
%	62%	57.14%	28.57%	38.10%
4 Marketing Availability				
(1) Distance to higher voltage power lines	1	3	1	0
(2) Terrain of power line	1	2	2	3
(3) Terrain of development	1	2	1	3
(4) Distance from well to plant site	0	0	0	0
(5) Proximity to market factors	0	3	1	3
Fractional Score:15 Points	**3**	**10**	**5**	**9**
%	20%	66.67%	33.33%	60%
Total Score: 60 Points	**30**	**43**	**28**	**34**

The ultimate score of each potential area was calculated by adding the four fractional values of all factors as shown in Table 5 and 6. Figure 44 shows the resource sites with the total scores. The highest scores mean the most remarkable development potential for the field. Ultimately the Republic of Sudan's potential areas ranking as following Bayuda (43 out of 60), Muglad rift basin (34 out of 60), Jebel Mara (30 out of 60), and Red Sea (28 out of 60).

Table 6 Summary of positive attitude factors total scores (in percent) separated by areas and availability fractions.

Areas	**Jebel Mara**	**Bayuda**	**Red Sea**	**Muglad Basin**
1. Land	53.33%	80.00%	73.33%	73.33%
2. Exploration	66.67%	100.00%	66.67%	66.67%
3. Reservoir	62.00%	57.14%	28.57%	38.10%
4. Marketing	20.00%	66.67%	33.33%	60.00%

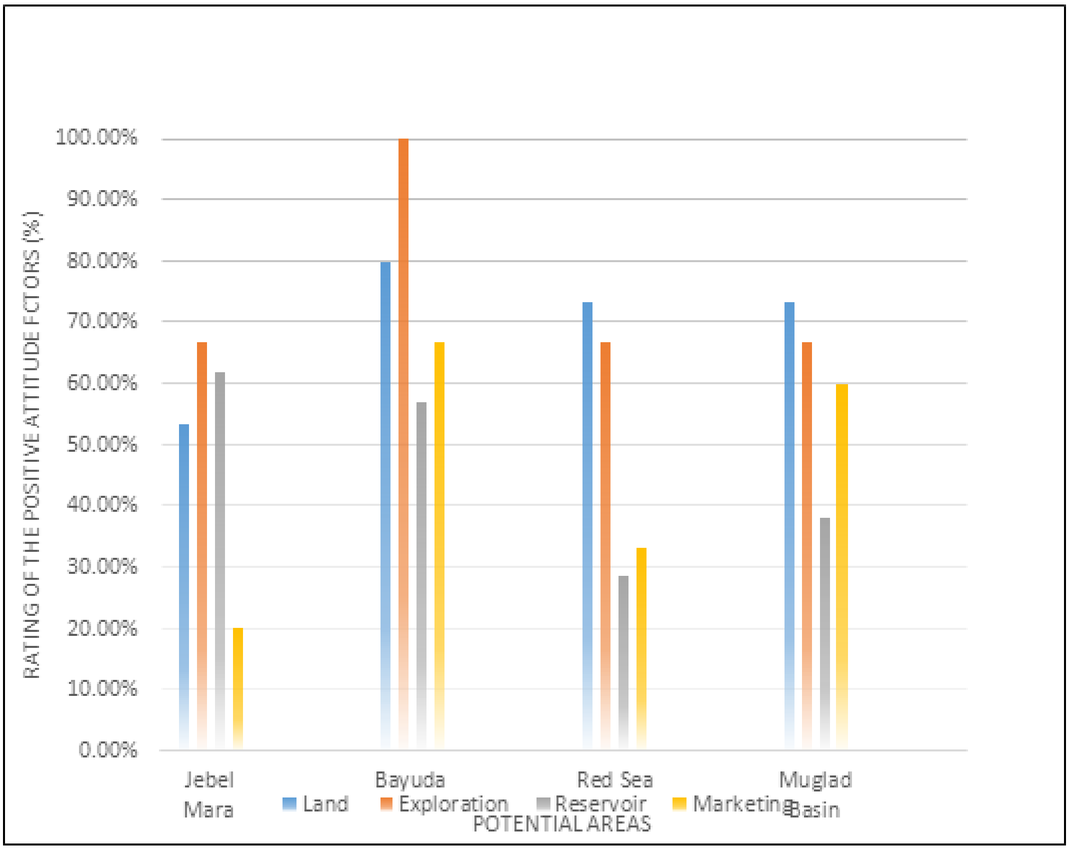


Figure 44 Rating of potential geothermal areas with positive attitude factors; Jebel Mara, Bayuda volcanic field, Red Sea area, and Muglad Rift Basin

4.1.2 Final Ranking

As mentioned before, in this stage, all four fractions will be integrated rather than the sum of all positive attitude factors to highlight the significance of all four fractions. Therefore, cut off values were applied to the scores of all the four fractions shown in Table 6 and Figure 43. At this stage, the percentage and cut off values of each fractional score for the exploration and land factors were set at 80%, while the cut off for the marketing and reservoir factors was 55% due to a lack of data. Applying here a cut off value of 80% would produce almost no results and thus would not follow the objective using as many data and information as possibly available. The results then shown in Table 7 can be classified into three ranking levels: I, II, III, and IV as presented in the following:

Bayuda is ranked as level I, which represents the highest level where future research budgets and financial investments for geothermal exploration and drilling should be discussed to prove the potentiality and commerciality of the resource because almost all required data is available. KenGen pointed out two prospects for drilling in BVF.

Table 7 Final ranking of the most potential geothermal areas in Sudan (PGRAS).

Positive attitude factors		PGRAS			
	Cut off value	**Jebel Mara**	**Bayuda**	**Red Sea**	**Muglad Basin**
1. Land uses availability	≥80%		X		
2. Past Exploration availability	≥80%		X		X
3. Reservoir availability	≥55%	X	X		
4. Marketing available	≥55%		X		X
	Ranking Level	**III**	**I**	**IV**	**II**

Muglad Basin is ranked as level II. Further research money and investments for geothermal exploration should focus on conducting detailed studies and analyses to evaluate the potentiality and determine the prospect area.

Jebel Mara and *Red Sea* are rated level III and level IV, respectively, the lowest one. There is insufficient basic information to support any decision in these potential areas. Reconnaissance surface survey and or applied geophysical methods such as a suite of carefully designed electrical surveys direct current (DC) resistivity or transient electromagnetics (TEM), Magnetotellurics (MT) are required to evaluate potentiality and figured out the prospect areas for drilling.

The ranking levels of I to IV in Table 2 can be translate in following possible policy recommendations with:

(I) Site where future research money and monetary investments for geothermal exploration should be direct into drilling wells in the prospect areas.

(II) Site where advanced research budgets should be direct to the detailed study and analysis based on existing data of the oil companies operating the Basin to evaluate the potentiality and figure out the prospect area.

(III) The site where exploration activities such as detailed geological and geophysical surveys should be directed to figure out the prospect area and the reservoir depth for the drilling stage.

(IV) The site where advanced research budgets and investments should be directed to carry out geological, geochemical and geophysical surveys to figure out the structures and infer the conceptual model of the potential area.

This ranking is subjective because it is based on qualitative evaluations conducted by researchers. Therefore, this assumption may be incorrect or biased to some extent, or it may not accurately exhibit the current situation. More precise data would be favored because many assumptions, such as reservoir depth and flow rates, are employed for individual site assessments. In addition, specific sub-criteria such as reservoir temperature and prospect location needs to be identified to determine the most convenient area for further exploration and predict the utilization type. In the other words Table 7 demonstrates the priority for geothermal development to the potential geothermal fields in Sudan by assessing them according to the available data.

Bayuda volcanic field or prospect would be the best for drilling exploration to test and confirm the occurrence of the geothermal resource. Sudan only produces oil from the Muglad rift basin, and many companies are working on it; therefore, tremendous data is available from oil wells. This data allows us to investigate and examine the source of the high geothermal gradient detected by the oil wells. Oil wells existing and available data save a high percentage of exploration cost and should be optimized to establish a good understanding of the basin from a geothermal perspective. Available data indicated Jebel Mara is a potential geothermal resource, and it has favorable features such as a) setting of the general regional geology; b) possible presence source of heat which represent in magma chambers at a more or less shallow depth; c) volcanism, recent and historical activities; d) occurrence of geothermal manifestations in the area; evidence of possible geothermal activities; and good meteoric recharge, which indicated by hydrochemical analysis of geothermal water. The temperatures output of the hot springs suggests this could be a medium temperature resource. The hot springs occurrences could be discharging along a narrow fracture. Therefore, Jebel Mara required a detailed geological and geophysical survey to determine the prospect area and the reservoir depth for the drilling stage. The Red Sea Coastal area has valuable information such as anomalies of temperature gradients and geo-pressurized revealed from oil wells. The offshore area seems more potential than the onshore area, which requires high exploration costs. Durwara Island, a few kilometers offshore, is the most potential area based on the encountered bottom hole temperature, which exceeds 190 °C. Thereby, more exploration activities should be carried on to determine an improved conceptual model.

4.2 Expert opinion

In various scientific studies expert opinions or even expert panels are used for the final analysis and conclusions, e.g. [71]. This tool is used across disciplines, from medicine over environmental management to technical aspects. However, often the expert tool is applied related to topics involving risks, as here the factor 'experience' is of main importance, e.g. [72, 73]. However, other authors outline that involving experts might undermine the role and views of other stakeholders [74].

In this study expert opinion was considered as a method by finally dismissed as the judgment is more on a technical level often with measurable items. Further, the author of this work is an expert on the study area Sudan, which is required as many if not all items assessed are site specific. Therefore, without further outside experts the here derived results shown above and final conclusion below are valid.

4.3 Conclusions

The geothermal resources assessment of Sudan indicates that Sudan has various potential areas that are promising for exploration. Based on the available data outlined here, the assessment and ranking would surely save cost and time, and encouraging the decision-makers to explore further.

The study has focused on assessing and ranking the potential areas in Sudan to mitigate the risk accompanied by the exploration phase. The assessment that has been done is aimed to guide the decision-makers on which basis assessment to prioritize the most convenient area for further exploration and identify the missed data to consider before any decision. Moreover, this study's findings help mitigate the uncertainties and increase the chance of success for the further exploration activities of Sudan's geothermal resources. The ranking of geothermal fields is not very strong (due to uncertainties and the quality of data applied), but it is strong enough to present some quantitative assessment, which can be more easily turned into economic costs and financial risks.

Many fields and more data were used to apply the positive attitude factors design method in Thailand, but in Sudan, many factors or parameters were not available, and only four potential areas were targeted for assessment. Sudan's geothermal resources, although was reported in the 1960s but still in an early stage. Therefore, the assessment will mitigate geothermal risk to attract funds and facilitate and accelerate geothermal development for the Republic of Sudan. The overall result of this assessment will encourage public and private sector investment into geothermal utilization.

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